NAVPERS 93400 A-1a

FUNDAMENTALS OF ELECTRONICS

VOLUME 1a

BASIC ELECTRICITY

Direct Current

Bureau of Naval Personnel

PREFACE

This book is part of a nine-volume set entitled "Fundamentals of Electronics." The nine volumes include:

Volume 1a - NavPers 93400A-1a, Basic Electricity, Direct Current
Volume 1b - NavPers 93400A-1b, Basic Electricity, Alternating Current
Volume 2 - NavPers 93400-2, Power Supplies and Amplifiers
Volume 3 - NavPers 93400-3, Transmitter Circuit Applications
Volume 4 - NavPers 93400-4, Receiver Circuit Applications
Volume 5 - NavPers 93400-5, Oscilloscope Circuit Applications
Volume 6 - NavPers 93400-6, Microwave Circuit Applications
Volume 7 - NavPers 93400-7, Electromagnetic Circuits and Devices
Volume 8 - NavPers 93400-8, Tables and Master Index

If you are becoming acquainted with electricity or electronics for the first time, study volumes one through seven in their numerical sequence. If you have a background equivalent to the information contained in volumes one and two, you are prepared to study the material contained in any of the remaining volumes. A master index for all volumes is included in volume eight. Volume eight also contains technical and mathematical tables that are useful in the study of the other volumes.

A question (or questions) follows each group of paragraphs. The questions are designed to determine if you understand the immediately preceding information. As you study, write out your answers to each question on a sheet of paper. If you have difficulty in phasing an answer, restudy the applicable paragraphs. Do not advance to the next block of paragraphs until you are satisfied that you have written a correct answer.

When you have completed study of the text matter and written satisfactory answers to all questions on two facing pages of the book, compare your answers with those at the top of the next even-numbered page. If the answers match, you may continue your study with reasonable assurance that you have understood and can apply the material you have studied. Whenever your answers are incorrect, restudy the applicable material to determine why the book answer is correct and yours is not. If you make an honest effort to follow these instructions, you will have achieved the maximum learning benefits from each study assignment.

Follow the directions of your instructor in answering the review questions included at the end of each chapter.

CHAPTER 1

MEASUREMENT AND STRUCTURE OF MATTER

It is impossible to pinpoint the precise moment in history when man stopped wandering about the earth in search of food and shelter and began reflecting upon the forces that governed his existence. His first feeble attempts to understand his environment became the basis for science.

If there are roots to Western science, they no doubt lie under the rubble that was once ancient Greece. The Greeks reasoned that the earth was a sphere, that substances must have a basic particle, and even proposed a crude atomic theory. Unfortunately, they were not prone to self-criticism and did not practice a system of rigid experimentation. Man will never know if there were any universal truths postulated by these early Greeks, for as time passed into the "Middle Ages," most information of a scientific nature was lost due to neglect and ignorance.

The millennium between 486 AD and the end of the 15th century is commonly referred to as the "Dark Ages." They were dark because the brilliance of human reason fell prey to the superstition and mysticism that ran rampant through Europe at that time. The fact that science was kept alive at all was mainly due to the ancient craft known as alchemy. The alchemist spent most of his time searching for some magic process whereby he could turn base metals into gold. Although his search was fruitless, he did through recorded data, provide some useful information and very fertile ground for the inquisitive men we now call scientists. If the ties of superstition are ever completely severed, credit for the initial incision would no doubt be given to two early giants of modern science—Galileo and Newton. It was with them that the scientific revolution began.

1-1. Matter and Mass

Matter is most often defined as "anything that has mass and occupies space." It is relatively easy to form a mental image of some object as it occupies space. The meaning of mass, however, may not be quite so obvious. Mass is best defined as "the property of matter that gives it inertia or opposition to a change in state of motion or rest."

The terms weight and mass can be used synonymously on earth, especially at sea level. The difference between mass and weight is that the mass of an object is the same anywhere in the universe but its weight is not. This difference is apparent to our astronauts as they travel through outer space. A man possessing a definite amount of mass might weigh 150 lbs. at the surface of the earth but would be weightless in an orbiting satellite. This fact illustrates that a body of matter can have mass without weight but weight always indicates the presence of mass. Weight is actually a measure of the gravitational force pulling a mass toward the center of the earth.

Q1. Why is matter defined in terms of mass rather than weight?

MATTER AND MEASUREMENT

1-2. The Importance of Measurement

Practically every field of science deals in some way with either the structure or the measurement of matter. If one of our modern scientists were asked to select what he considered to be the most important single factor in the rapid advance of present day civilization, he might well choose the ability to measure quantities accurately. Without realizing it, practically every act of our daily lives involves measurement of some kind. In driving to work or school, our speed is measured in miles per hour. Upon arriving at our destination, we determine whether or not we are late by looking at a clock—the instrument of time measurement. How handicapped the chemist would be if he could not measure the myriad quantities of chemicals in his experiments. Picture the chaotic results of a carpenter's efforts if he could not measure the length of the timbers used in constructing a home. So important is the ability to measure, that one of Britain's great scientists, Lord Kelvin, believed that unless a person can describe the topic of his study with measurements, he knows nothing about that topic. Since measurement is the very foundation of the study of electricity and electronics, it will be discussed next.

A1. Mass remains constant throughout the universe, weight does not.

1-3. Mechanics of Measurement

Basically all measurements, regardless of type, are accomplished in the same way. To make a measurement, one must compare the dimensions of the quantity to be measured with the dimensions of a known standard quantity. The quantity to be measured is then said to be so many times larger or smaller than the known standard quantity.

Any measurement can be divided into two parts. The first part tells how many times larger or smaller the unknown quantity is, and the second part tells the standard or reference used for comparison. As an example, assume that a half-back runs the length of a football field in ten seconds. From this measurement, his running time is determined to be ten times greater than the standard or reference—one second. This comparison of the half-back's time to the time of one second tells how long it takes him to run the length of the field.

To make measurements meaningful to other people, a reference must be used which has one exact meaning to all who use it. In the above example, everyone concerned with the measurement must agree on the length of time of one second, otherwise "ten seconds" would indicate a different amount of time to each person.

Q2. Is it possible to make a measurement without using a standard? Explain.

The British realized the need for exact and standard references. According to legend, one of England's many monarchs attempted to develop a system of standardization in which he, the king, was the standard. A common unit of measure, the FOOT, was developed by this king. His own foot was the physical standard of reference, but unfortunately this standard was made unavailable upon the death of the king. Another standard developed by this man was the ROD. A rod equalled the length of a line composed of twenty lords who stood chest to back. But, again unfortunately, the lean years shrunk the rod while the bountiful years stretched it and thus the "standard" took on different meanings at different times. Overlooking these minor difficulties this king had great foresight, for his idea of standard units is used today. Though many systems of measurement have been devised, only the metric system and the British system will be considered in this text.

1-4. The Metric System

Let us now examine a particular system of measurement, namely, the metric system. This system is used by most European countries and by scientists throughout the world. Any system used for the measurement of matter is ultimately based on three basic dimensions: length, mass, and time. Scientists use a form of the metric system known as the METER-KILOGRAM-SECOND (mks) SYSTEM in which the unit of length is the meter, the unit of mass is the kilogram, and the unit of time is the second.

The METER was originally defined as one ten millionth of the distance along a meridian extending from the North Pole, through Paris, to the Equator. At the time of this definition a physical model was created and housed at the International Bureau of Weights and Measures, Sevres, France. The physical standard is made of a platinum-iridium alloy bar upon which two marks are etched. The distance between the two marks, when the bar is at the temperature of melting ice, is one meter. Modern investigation shows that this physical model varies slightly from time to time and is therefore not truly accurate. At present, however, this bar remains the physical standard, although in the near future scientists may adopt a new and unvarying standard based on the length of one wave of a specific kind of light energy.

The KILOGRAM uses as its standard a block of platinum-iridium alloy called the INTERNATIONAL PROTOTYPE KILOGRAM also preserved at Sevres, France. The kilogram is based on the gram (1/1000 of a kilogram), originally defined as: the mass of one cubic centimeter of pure water measured at 4° centigrade. This temperature was chosen because near 4° centigrade the density of water is practically independent of temperature.

The SECOND is defined as 1/86,400 of a mean solar day, the mean solar day being the average time required for the earth to make one rotation on its axis while revolving about the sun. In recent years it has been found that this standard also has irregularities and in the near future an atomic clock based on the vibration of a cesium atom may be adopted.

A sub-division of the metric system is known as the CENTIMETER-GRAM-SECOND (cgs) SYSTEM, in which sub-multiples of the meter and kilogram are used. A CENTIMETER is one hundredth of a meter; the gram and second were explained previously.

Q3. Would a butcher's scale used to weigh meat be considered a standard?

1-5. Convinent Units

In many situations the quantities to be measured may be extremely large or extremely small, and the basic units may prove too cumbersome for ease of manipulation. For example, the length of our galaxy, the Milky Way, is approximately 946,800,000,000,000,000,000 meters. It should also be kept in mind that, compared to other astronomical distances, the length of the Milky Way is small. Thus, to the astronomer the unit METER is not convenient. A much more meaningful description of this distance would be 100,000 LIGHT YEARS where the light year is defined as the distance light travels in one year.

In the metric system a prefix is attached to one of the basic units to provide a unit more consistant with the dimensions of the quantity involved. A list of the commonly used prefixes and their meanings is given in Table 1-1. A common example of the use of prefixes is the microsecond which is one millionth of a second.

PREFIX	ABBR	POWER OF TEN	VALUE
TERA	T	10^{12}	MILLION MILLION
GIGA	G	10^{9}	THOUSAND MILLION
MEGA	M	10^{6}	MILLION
KILO	K	10^{3}	THOUSAND
HECTO	h	10^{2}	HUNDRED
DECA	dk	10^{1}	TEN
-	-	10^{0}	ONE
DECI	d	10^{-1}	TENTHS
CENTI	c	10^{-2}	HUNDREDTHS
MILLI	m	10^{-3}	THOUSANDTHS
MICRO	u	10^{-6}	MILLIONTHS
NANO	n	10^{-9}	THOUSAND MILLIONTHS
PICO	p	10^{-12}	MILLION MILLIONTHS
FEMTO	f	10^{-15}	-
ATTO	a	10^{-18}	-

Table 1-1 - Prefixes

1-6. British Gravitational System

A second system, the one common to this country and Great Britain, also deserves mention. This system, known as the FOOT-POUND-SECOND (fps) SYSTEM is the one with which the average person in this country is most familiar. The fps system differs from the metric system in that the pound is not a unit of mass as is the kilogram, but is a unit of force. The unit of mass in the fps system is the slug which is equal to approximately 14.6 kilograms. Formerly, standards were maintained for the fps system; but now all these units are defined in terms of metric standards. The relationship between metric and British units are shown in Table 1-2.

METRIC TO BRITISH	BRITISH TO METRIC
1km. = 0.62137 mi.	1 mi. = 1.6093 km.
1m. = 3.2808 ft.	1 ft. = 0.3048 m.
1cm. = 0.3937 in.	1 in. = 2.5400 cm.
1kg. = 2.2046 lb.	1 lb. = 0.4536 kg.
1gm. = 0.0353 oz.	1 oz. = 28.3490 gm.

Note: The metric mass units are equated to the force in pounds that they would exert at sea level on earth.

Table 1-2 - Comparison of Units

In the following sections these units and techniques will be used to good advantage in studying the characteristics and structure of matter.

LIGHT, HEAT, AND PRESSURE

1-7. Measurement of Light

The study of light has provided man with a fascinating but most perplexing problem in science. Man has learned to generate, control, and measure light energy very effectively. Through measurements of the faint light coming from distant stars and planets man has learned practically all that is now known about the objects in outer space. Unfortunately the exact structure of light is still a mystery. It is well known that light is a form of energy, but the physical form in which this energy exists is not known. Nevertheless, two theories have been advanced concerning the nature of light.

One of these theories proposes the existence of light as tiny packets of energy called PHOTONS. Photons can contain various quantities of energy, the amount being dependent upon the color of the light involved. Photons of light at the blue-violet end of the spectrum contain more energy than photons of red light.

The second theory pictures light rays as consisting of ELECTROMAGNETIC WAVES of very short length. There is strong evidence to indicate that light may exist in either of the above states, depending on the conditions under which it is observed. If this is true, there is no single model which can be constructed to illustrate the dual nature of light.

A2. No. Measurement cannot exist without a standard.

A3. No. A scale is calibrated against a standard weight, but the scale is not a standard.

One of the more important measurements associated with light energy is that of WAVELENGTH measurement. Light may be analyzed by assuming it consists of waves similar to the ripples which are generated when a ball is dropped into a pool of water (see Figure 1-1). The waves which are generated consist of a number of CYCLES such as the one shown between points A and B. In travelling from A to B the wave has gone through all of its possible variations and therefore has completed an entire cycle of events. In travelling from B to C the wave would simply repeat the variations that occurred between A and B. The number of these complete cycles per second is called the FREQUENCY of the wave. If the wave illustrated completes one cycle in one twentieth of a second, it would have a frequency of twenty cycles per second.

The distance between a point on wave (A) and a corresponding point on an adjacent wave (B) is called the WAVELENGTH of the wave. Wavelength may be measured in any of the distance units described previously such as inches, feet, meters, or centimeters, etc. Light waves have extremely short wavelengths of less than one millionth of an inch. Figure 1-2 shows the wavelength in centimeters (cm) of various types of electromagnetic waves including light waves.

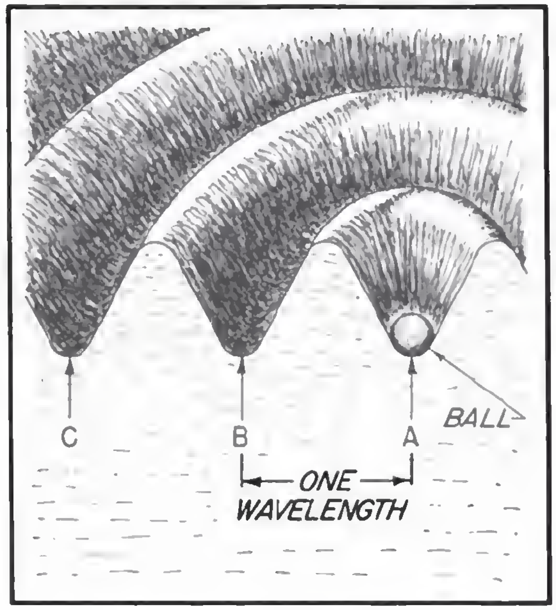

Figure 1-1 - Concept of wavelength.

1-8. Measurement of Heat

Heat is a form of radiant energy very similar in nature to light. For many purposes, heat energy (often called thermal energy) may be considered to be light energy of a wavelength too long for detection by the human eye. Heat energy, like light energy, is often thought to be present in all materials in small massless packets called PHONONS (also called quanta). The number of phonons present in a material is directly related to temperature. Heat energy can be obtained as a result of chemical reactions, nuclear reactions, friction, and electrical energy.

Q4. A piece of metal is deposited in a scrapyard. Does this material possess energy? If so, describe the energy.

The quantity of heat a substance contains is normally measured in one of the following basic units: a CALORIE, which is the quantity of heat necessary to raise the temperature of one gram of water one degree centigrade, or the BRITISH THERMAL UNIT, which is the quantity of heat

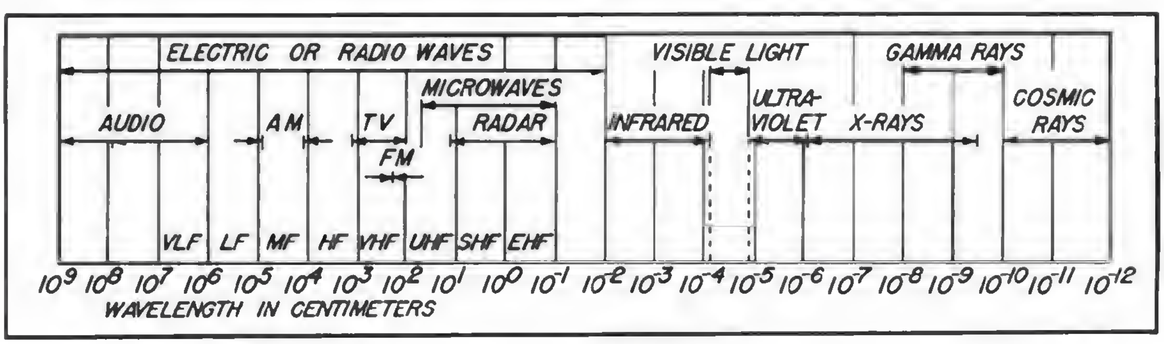

Figure 1-2 - Electromagnetic wavelengths.

necessary to raise the temperature of one pound of water one degree Fahrenheit.

From the above definitions it may be determined that the TEMPERATURE of an object is by no means a measure of the amount of heat it contains. A small quantity of water in a test tube can be raised a degree in temperature by the heat from a wooden match. In contrast, consider the great amount of heat required to raise the temperature of the water in a swimming pool one degree. It is evident that these two quantities of water, while they may be at the same temperature, contain vastly different quantities of heat. Temperature indicates the extent to which a body has been heated, rather than the amount of heat which it contains. Although many scales have been designed for the measurement of temperature, only the CELSIUS (more commonly called CENTIGRADE scale) and the FAHRENHEIT scales will be discussed here. The main differences between the two scales illustrated in Figure 1-3 are the values arbitrarily assigned to the freezing and boiling points of water. On the centigrade scale the freezing and boiling temperatures are 0 degrees and 100 degrees respectively, while on the Fahrenheit scale they are 32 degrees and 212 degrees respectively. Equations for conversion from Fahrenheit to centigrade or from centigrade to Fahrenheit can be found in most physics books and will not be presented here.

1-9. Measurement of Force

Although the word force usually causes a person to form a mental image of some type of mechanical system, the origin of many forces is electrical in nature. The operation of the electrical motors in vacuum cleaners, refrigerators, and other home appliances is entirely dependent upon the interaction of electrical forces. As force occupies such a prominent position in the theory of electrical devices, a knowledge of the units used to measure force is a necessity.

Specifically, force is defined as "that quantity which causes acceleration (change in motion) of a material body." The POUND, a unit with which we are all familiar, is the unit of force in the British system. A pound is the amount of force necessary to impart an acceleration of one foot per second to a mass of one slug.

In the mks system the force unit is the NEWTON (nt) and is defined as "that force which will give a mass of one kilogram an acceleration of one meter per second per second. Thus, a newton would be the approximate force felt on one's hand while holding a one-quarter pound package of butter.

In the cgs system the unit of force is the DYNE. One dyne is the amount of force that will give a mass of one gram an acceleration of one centimeter per second per second. A dime coin held on the finger tips would exert a downward force of about 2450 dynes. This example indicates that the dyne is a rather small unit of force. Figure 1-4 shows a comparison between the newton, the dyne, and the pound.

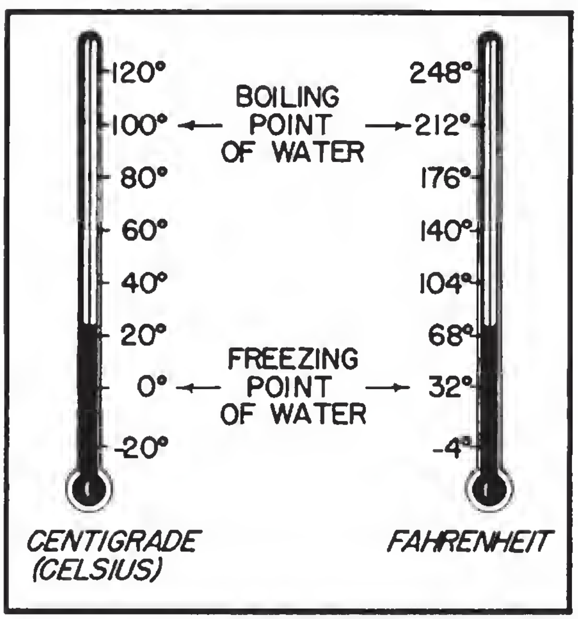

Figure 1-3 - Temperature scales.

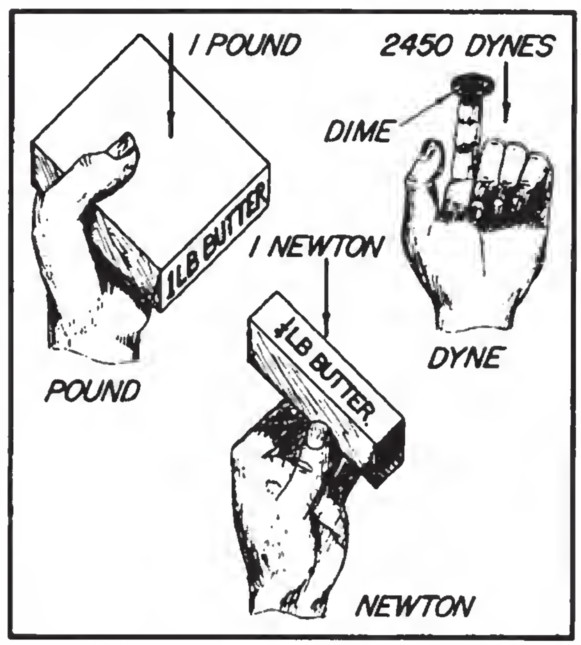

Figure 1-4 - Comparison of force units.

A4. Yes. Energy is present in the form of photons and phonons.

1-10. Measurement of Pressure

Another quantity which acts on matter is pressure. Pressure is defined as "force per unit area," and is expressed as a force unit divided by an area unit. Thus, pressure may be expressed as pounds per square inch, dynes per square centimeter, etc.

Q5. What is wrong with the statement: The pressure is two kilograms per square meter?

The atmosphere surrounding the earth exerts a pressure of approximately 14.7 pounds per square inch on the surface of an object placed at sea level. This normal sea level pressure is sometimes used as a unit of pressure called an ATMOSPHERE (atm). One atmosphere is therefore a unit of pressure equal to approximately 14.7 pounds per square inch. Pressure may also be measured in BARS or MICROBARS. One bar is equal to 14.5 pounds per square inch or one million dynes per square centimeter.

Pressure may also be measured by comparing it to the pressure exerted by a column of mercury. Thus, a pressure may be stated as 7 MILLIMETERS (mm) of mercury, indicating a pressure equal to that exerted by a column of mercury 7 millimeters high. Similarly, a pressure of 10 CENTIMETERS (cm) of mercury would be the pressure exerted by a column of mercury 10 centimeters high. Over the years many different units have been devised for the measurement of pressure. However, the ones listed above are the most common.

GROSS CHARACTERISTICS OF MATTER

1-11. States of Matter

Matter is known to exist in three states: gas, liquid, and solid. Matter in the gaseous state will conform perfectly to the shape of its container. It possesses neither a fixed shape nor a fixed volume. Some common examples of gases are: the atmosphere which we breathe, the carbon dioxide which we exhale, and water vapor.

A liquid differs from a gas in that it has a fixed volume. It is similar to a gas in the respect that it has no fixed shape, and will conform to the shape of its container. Examples of common liquids are: water, petroleum, and mercury.

In the solid state matter has a fixed shape and volume. Common solids are: iron, quartz, and carbon.

Q6. Tell how the atmosphere can easily be proven to follow the definition of matter.

1-12. Change of State

One of the fundamental properties of matter is its ability to change state. A change of state is most conveniently observed in the substance known as water. We are all familiar with the fact that water which is normally a liquid is easily converted to a solid (ice) or, to a gas (steam). A moments consideration of the three states of water indicates that some external influence must be involved in producing a change of state. Extending our reasoning along this line, the first thing that comes to mind is that steam is very hot, and ice is very cold. From this, one may correctly assume that heat is one of the factors involved in a change of state. Water at a temperature of zero degrees Fahrenheit is solid ice. If the temperature is raised to thirty-two degrees Fahrenheit the solid ice becomes the liquid form of water. If the temperature is raised still higher to two hundred and twelve degrees Fahrenheit, the liquid vaporizes into the gas known as steam.

Q7. Is there any heat present in cold water? Explain.

A second factor involved in a change of state is pressure. If the temperature and pressure of oxygen are adjusted to the proper value, it can be made to exist as a liquid. At greater pressure and reduced temperature it will be converted to a solid. Since the properties of many substances are dependent on both temperature and pressure, a standard or reference is necessary. This reference condition is known as standard temperature and pressure (STP). or normal temperature and pressure (NTP), and is defined as a pressure of one atmosphere at a temperature of zero degrees centigrade.

Some materials such as dry ice and moth balls, change from the solid to the gaseous state without going through the liquid state. These materials are called sublime materials and the process by which this takes place is called sublimation.

INTERNAL STRUCTURE OF MATTER

1-13. Continuous Matter

With the exception of the Greeks, ancient

man had little interest in the structure of materials. He accepted a solid to be just that—a continuous uninterrupted substance. Some of the Greeks thought that if a person began to subdivide a piece of material such as copper, he could do so indefinitely. It was among these people that the idea of continuous matter was fostered. Others reasoned that there must be a limit to the number of subdivisions that one could make and still retain the original characteristics of the material being subdivided. They held fast to the idea that there must be a basic particle upon which all substances are built. Both of these arguments were equally valid at that time, for there was still no means available to determine which faction was correct. Mankind did not know the answer to this question until the nineteenth century.

It was not until 1805 that John Dalton proposed his theories concerning the nature and behavior of matter. He proposed that all matter is composed of invisible, solid, indestructible particles.

1-14. Composition of Matter

As previously stated, the efforts of the Greeks to subdivide a simple material were unsuccessful because of their limited technology. It was near the middle of the seventeenth century that Robert Boyle phrased the first definition of an elemental substance. He stated that an ELEMENT is a substance that cannot be decomposed into simpler substances. There are, at the time of this writing, one hundred and two known elements with the possibility of the discovery of many more. They range from the abundant elements such as silicon, carbon, and oxygen to the rare elements such as lanthanum, samarium, and tuletium which are extremely difficult to process. During World War II many elements were synthesized (man-made). The names of the man-made elements are interesting because in many cases they indicate their origin by their names. Elements such as americium, californium, and berkelium are examples of elements of this type.

To make the discussion of elements and the subsequent material more meaningful, a table of elements called the PERIODIC TABLE is provided in Appendix III. Notice that this table is separated into vertical and horizontal columns that form blocks into which are placed symbols that represent the one hundred and two different elements. The vertical columns are called groups, and the horizontal rows are called periods. The full significance of this table will be explained later, but a cursory description of the table is justified at this time. The symbol used for iron is (Fe). It is located in period four, group eight B. The symbol used to represent copper (Cu) is also in period four, but it is in group one (B). Notice that the elements in the (B) groups are all heavy metals, the elements in groups one and two (A) are light metals, and the elements in groups three to seven (A) are non-metals. The elements in group eight (A) are called the inert gases. They are called inert because they will not combine chemically with other substances. The elements boron, silicon, geranium, arsenic, antimony, tellurium, and polonium are called metalloids because under certain conditions they can possess the properties of metals and non-metals. The two remaining columns contain the lanthanide series which are the rare earth elements and the actinide series, part of which include the man-made elements 95 through 102.

Although many substances are composed of a single element, a far greater number of substances are composed of a combination of different elements. When two or more different elements are chemically combined, they form COMPOUNDS. A common example of a compound would be a substance such as water which is composed of the element hydrogen and the element oxygen. The process whereby the elements are chemically combined to form a compound is called SYNTHESIS. During the synthesis of water, one part of the oxygen element is combined with two parts of the hydrogen element. A compound once formed by synthesis can also be examined and broken down into its elements. This process of examination and reduction is known as ANALYSIS.

As elements such as hydrogen and oxygen are chemically combined to form a compound, they lose their individual identity. A most vivid realization of this fact can be noted when visualizing white crystalline sugar. This compound consists of the black, solid element carbon, and two colorless gaseous elements, oxygen and hydrogen. Thousands of compounds are known, each of which possesses definite chemcial and physical properties that enable it to be distinguishable from other compounds. The almost limitless combinations of elements to form compounds has led to discoveries of the many substances which have become a part of our daily lives. A few common examples of compounds are: salt, wood, and limestone.

When various elements or compounds are mechanically combined without the occurrence of a chemical change, the result is called a MIXTURE. The component elements or compounds of a mixture do not lose their chemical or physical properties. Though the mixture may acquire an appearance that differs from any of its parts, each ingredient that blends

A5. Pressure is force per unit area. The kilogram is a mass unit and not a unit of force.

A6. It exerts pressure, therefore it must have mass and occupy space.

A7. Yes. All matter contains packets of heat energy. The quantity of heat present in cold water (liquid state) is large when compared to that of ice (solid state).

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into forming the mixture will retain its identity. Thus, it is possible to easily separate a mixture into its individual parts.

There are two types of mixtures—heterogeneous and homogeneous. A heterogeneous mixture, such as may be formed by combining sand and gravel, is one which does not have a uniform blending of ingredients. Homogeneous mixtures are those that have a uniform composition such as homogenized milk or sugar dissolved in water. Homogeneous mixtures are called solutions.

Q8. A compound such as sulfuric acid (H_2SO_4), consisting of two parts hydrogen, one part sulphur and four parts oxygen, is chemically divided into its basic parts. How would you describe the resulting substance?

Q9. When sulfuric acid (H_2SO_4) and water are combined, each retains its separate identity. How would this substance be described?

The discovery of the many substances that have become a part of our lives would not have been possible without a great deal of study of the elements. Since the elements are the fundamental substance of all matter, the development of any new product must be based on a knowledge of these substances. The elements cannot be decomposed into a simpler substance; therefore, the dissimilarity between them can only be explained by assuming each element to consist of basic particles. This basic particle is called an ATOM. While the atoms of a given element are similar, the atoms of different elements will have different characteristics.

BASIC PARTICLES OF MATTER

1-15. The Atom

An atom is defined as the smallest particle of an element that retains all of the properties of the element. The following is Dalton's conception of the atom:

a. All materials are composed of minute indestructible particles called atoms.

b. The atom is the smallest component part of an element that enters into a chemical reaction.

c. All atoms of a given element are exactly the same in weight, shape, and size.

The atom is the smallest part of an element that enters into a chemical change, but it does so in the form of a charged particle. These charged particles are called IONS, and they are of two types—POSITIVE and NEGATIVE. A positive ion may be defined as an atom that has become positively charged. A negative ion may be defined as an atom that has become negatively charged. One of the properties of charged ions is that ions of the same charge tend to repel one another, whereas ions of unlike charge will attract one another. The term charge has been used loosely. At present, charge will be taken to mean a quantity of electricity which can be one of two kinds, positive or negative.

Q10. If an atom of the element iron were separated from the element, what would be the resulting substance?

1-16. Molecule

The combination of two or more atoms to form the smallest part of a compound comprises a structure known as a MOLECULE. For example, when the compound water is formed, two atoms of hydrogen and one atom of oxygen combine to form a molecule of water. A single molecule is very small and is not visible to the naked eye. Therefore, a few drops of water may contain as many as a million molecules. A single molecule is the smallest particle into which the compound can be broken down and still be the same substance. Once the last molecule of a compound is divided into atoms, the substance no longer exists.

An element, while being composed of like atoms, is also considered to have a molecular structure. The term molecule, when applied to an element, designates the minutest portion of an element that can exist under normal conditions and still retain the characteristics of the element. A molecule of an element most often contains only one atom, and is called a MONATOMIC molecule. Examples of monatomic molecules are molecules of iron, gold, and copper. There are some elements, however, whose molecules cannot exist under normal conditions

as monatomic and must consist of a combination of atoms. Molecules having two atoms are called DIATOMIC molecules. Examples of diatomic molecules are oxygen, hydrogen and nitrogen. The molecules of some elements called POLYATOMIC molecules are composed of many atoms. As an example, a molecule of sulphur contains as many as eight atoms.

All atoms of all elements are similar because their contents are alike. Atoms are composed of minute particles, the discovery and the characteristics of which will now be discussed. Atoms basically consist of ELECTRONS, PROTONS, and NEUTRONS.

Q11. Ordinary table salt (NaCl) consists of a chemical combination of one part of the element sodium (Na) for every part of the element chlorine (Cl). Describe the smallest quantity of this substance that could exist.

1-17. An Atomic Model

Once the basic constituents of the atom are known, an attempt can be made to construct a suitable atomic model. This model must accurately represent and be compatible with all of the facts known at the time the model is constructed. Dalton viewed the atom as a small indestructible sphere having the ability to become firmly attached to other atomic spheres. Later and more advanced experimentation proved that tiny charged particles could be removed from inside the atom. As a result, Dalton's model could no longer be considered satisfactory.

Thompson advanced the theory that atoms must have a structure since a fundamental particle may be extracted from them. He envisioned the atom as being a sphere in which were contained a sufficient number of positive and negative charges to make the overall charge of the atom neutral. Thompson's idea that the positive and negative charges were evenly distributed throughout a sphere was disproved in an experiment conducted by Sir Ernest Rutherford.

In this experiment, a narrow beam of alpha particles (positive double charged helium ions) was obtained from a sample of radium and directed through a small hole in a lead block toward a thin sheet of gold foil. If the atom were constructed as Thompson visualized, the positive alpha particles should have had their paths deflected by small amounts due to the positive charge distributed evenly through the atom. The results were hardly what was expected. Rutherford found that most of the alpha particles went right through the gold foil without being deflected at all. The remaining particles received large amounts of deflection, some as high as 180°. This could only be explained by assuming that all of the positive charge in the atom was concentrated in one area away from the negative charge. Any alpha particle coming close to this center of charge would be severely deflected, while one passing some distance away would go through the foil undeflected.

From the results of Rutherford's experiments, emerged our present concept of the structure of the atom. The atom is now believed to consist of a group of positive and neutral particles (protons and neutrons) called the NUCLEUS, surrounded by one or more negative orbital electrons. Figure 1-5 shows the arrangement of these particles for an atom of the element boron. This concept of the atom

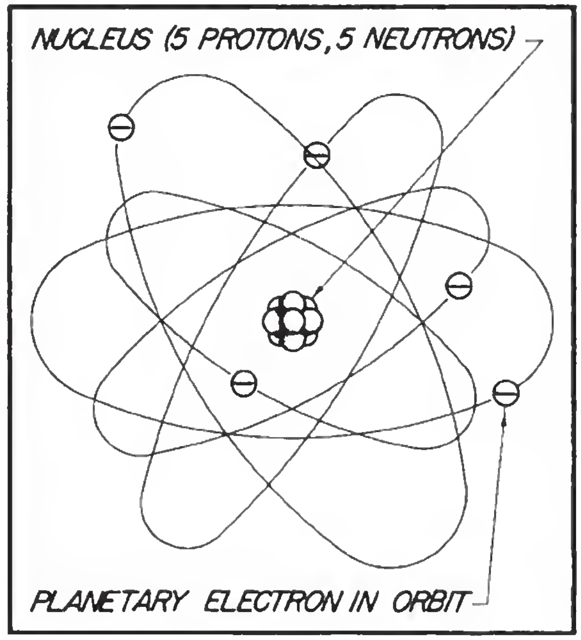

Figure 1-5 - Boron Atom.

can be likened to our solar system in which the sun is the massive central body, and the planets revolve in orbits at discrete distances from the sun. The nucleus commands a position in the atom similar to the position held by the sun in the solar system. The electrons whirl about the nucleus of the atom much as the planets whirl about the sun. In both the solar system and the atom practically all the matter in the system is contained within the central body.

SUB-ATOMIC PARTICLES

1-18. The Atomic Nucleus

Excluding particles such as mesons and

A8. The element hydrogen, the element sulphur, and the element oxygen.

A9. A mixture.

A10. The element iron.

A11. NaCl. A molecule of salt.

---

neutrinos, which are of little importance to electronics, the nucleus of an atom is made up of heavy particles called PROTONS and NEUTRONS. The proton is a tiny charged particle containing the smallest known unit of positive electricity. The neutron has no electrical charge.

In the lighter elements the nucleus contains approximately one neutron for each proton while in the heavier elements there is a tendency for the neutrons to out-number the protons. The nucleus of the helium atom consists of two protons and two neutrons. In contrast an atom of mercury has eighty protons and one hundred and twenty neutrons in its nucleus.

The mass of a proton and a neutron is very nearly the same and is equal to approximately 1.67×10^{-24} gram. This mass is about 1845 times as great as the mass determined for the electron.

To obtain some idea of the relative dimensions of a typical atom, assume the atom to be expanded in size until its outer diameter is equal to twice the length of a football field. The nucleus, positioned in the center, would appear as a sphere having a diameter equal to that of a penny! This example vividly illustrates the vast emptyness which exists within the atom. One can now readily see why most of Rutherford's alpha particles streamed through the thin gold foil with little or no deflection.

1-19. The Planetary Electrons

Surrounding the positive nucleus of a typical atom is a cloud of negative charge made up of planetary electrons. Each of these electrons contains one unit of negative electricity equal in amount to the unit of positive electricity contained in the proton. In a normal atom the number of electrons in this cloud is exactly equal to the number of protons in the nucleus. The net charge of a normal atom is therefore zero, since the equal and opposite effects of the positive and negative charges balance one another.

If an external force is applied to an atom one or more of the outermost electrons may be removed. This is possible because the outer electrons are not attracted as strongly to the positive nucleus as are the inner electrons. When atoms combine to form an elemental substance, the outer electrons of one atom will interact with the outer electrons of neighboring atoms to form bonds between the atoms. These atomic bonds constitute the binding force which holds all matter together. When bonding occurs in some substances, each atom retains its full complement of electrons. In other substances one or more outer electrons will be gained or lost as a result of bonding. As indicated by the above statements, the electron configuration of the atom is of great importance. The chemical and electrical properties of a material are almost wholly dependent upon the electron arrangement within its atoms.

As might be expected, the nucleus is well shielded by the electron cloud and does not enter into chemical or electrical processes. To disrupt the nucleus of an atom requires a vast amount of energy such as is released by each atom in the explosion of an atomic bomb.

Q12. Which would affect the mass of an atom to the greatest extent, the removal of a proton or the removal of all its electrons?

ATOMIC ANATOMY

1-20. An Elementary Atom

The intimate structure of an atom is best explained by a detailed analysis of the simplest of all atoms, that of the element hydrogen. The

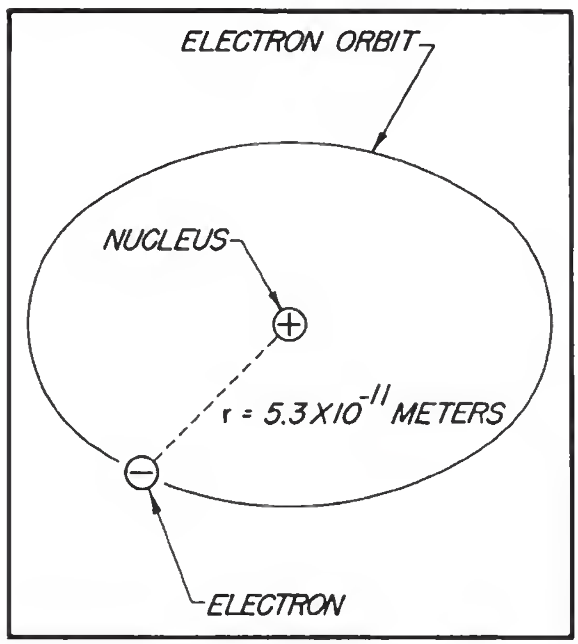

Figure 1-6 - The hydrogen atom.

hydrogen atom is composed of a nucleus containing one proton and a single planetary electron. According to a concept developed by Niels Bohr (Figure 1-6), the electron travels about the nucleus in a circular orbit having a fixed radius "r". As the electron revolves around the nucleus it is held in this orbit by two counteracting forces. One of these forces is called CENTRIFUGAL FORCE, and is the force which tends to cause the electron to fly outward as it travels around its circular orbit. This is the same force which causes a car to roll off a highway when rounding a curve at too high a speed. The second force acting on the electron is CENTRIPETAL FORCE. This force tends to pull the electron in towards the nucleus and is provided by the mutual attraction between the positive nucleus and negative electron. At some given radius "r" the two forces will exactly balance each other providing a stable path for the electron. For the hydrogen atom this radius is approximately 5.3×10^{-11} meter.

1-21. Energy Levels

Since the electron in the hydrogen atom has both mass and motion it contains two types of energy. By virtue of its motion the electron contains KINETIC energy. Due to its position it also contains POTENTIAL energy. The total energy contained by the electron (kinetic plus potential) is the factor which determines the radius of the electron orbit. The orbit shown in Figure 1-6 is the smallest possible orbit the hydrogen electron can have. In order for the electron to remain in this orbit it must neither gain nor lose energy.

In section 1-7 it was stated that light energy exists in tiny packets or bundles of energy called photons. Each photon contains a definite amount of energy depending on the color (wavelength) of light it represents. Should a photon of sufficient energy collide with the orbital hydrogen electron, the electron will absorb the photons energy as shown in Figure 1-7. The electron which now has a greater than normal amount of energy will jump to a new orbit farther from the nucleus. The first new orbit to which the electron can jump has a radius four times as large as the radius of the original orbit. Had the electron received a greater amount of energy, the next possible orbit to which it could jump would have a radius nine times the original. Thus, each orbit may be considered to represent one of a large number of energy levels that the electron may attain. It must be emphasized that the electron cannot jump to just any ORBIT. The electron will remain in its lowest orbit until a sufficient amount of energy is available, at which time the elec-

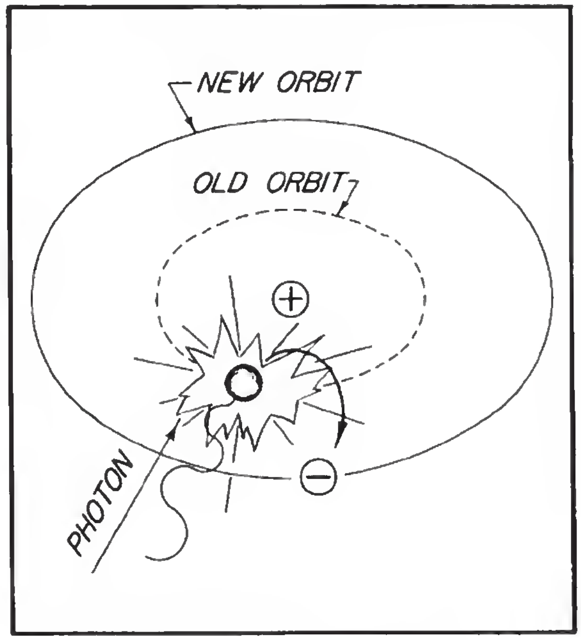

Figure 1-7 - Excitation by a photon.

tron will accept the energy and jump to one of a series of PERMISSIBLE orbits. An electron cannot exist in the space between permissible orbits or energy levels. This indicates that the electron will not accept a photon of energy unless it contains enough energy to elevate the electron to one of the allowed energy levels. Heat energy and collisions with other particles can also cause the electron to jump orbits.

Once the electron has been elevated to an energy level higher than the lowest possible energy level, the atom is said to be in an EXCITED state. The electron will not remain in this excited condition for more than a fraction of a second before it will radiate the excess energy and return to a lower energy orbit. To illustrate this principle assume that a normal electron has just received a photon of energy sufficient to raise it from the first to the third energy level. In a short period of time the electron may jump back to the first level emitting a new photon identical to the one it received.

A second alternative would be for the electron to return to the lower level in two jumps; from the third to the second, and then from the second to the first. In this case the electron would emit two photons, one for each jump. Each of these photons would have less energy than the original photon which excited the electron and would represent a longer wavelength of light.

This principle is used in the fluorescent light where ultraviolet light photons, which are

A12. Removal of a proton.

not visible to the human eye, bombard a phosphor coating on the inside of a glass tube. The phosphor electrons in returning to their normal orbits emit photons of light that are of a visible wavelength (longer wavelength). By using the proper chemicals for the phosphor coating any color of light may be obtained, including white (all colors combined). This same principle is also used in lighting up the screen of a television picture tube.

1-22. Complex Atoms

Although hydrogen has the simplest of all atoms, the basic principles just developed apply equally well to the atoms of more complex elements. The manner in which the orbits are established in an atom containing more than one electron is somewhat complicated and is part of a science known as quantum mechanics. In an atom containing two or more electrons, the electrons interact with each other and the exact path of any one electron is very difficult to predict. However, each electron will lie in a specific energy band and the above mentioned orbits will be considered as an average of the electrons positions.

1-23. Shells and Subshells

The difference between the atoms, insofar as their chemical activity and stability is concerned, is dependent upon the number and position of the particles included within the atom. Atoms range from the simplest, the hydrogen atom containing one proton and one electron, to the very complex atomic structures such as silver containing forty-seven protons and forty-seven electrons. How then are these electrons positioned within the atom? In general, the electrons reside in groups of orbits called shells. These shells are elliptically shaped and are assumed to be located at fixed intervals as predicted by the Bohr concept. Thus, the shells are arranged in steps that correspond to fixed energy levels. The shells, and the number of electrons required to fill them, may be predicted by the employment of PAULI'S EXCLUSION PRINCIPLE. Simply stated, this principle specifies that each shell will contain a maximum of $2n^2$ electrons, where (n) corresponds to the shell number starting with the one closest to the nucleus. By this principle the second shell for example, would contain $2(2)^2$ or 8 electrons when full. In addition to being numbered, the shells are also given letter designations as pictured in Figure 1-8.

Starting with the shell closest to the nucleus

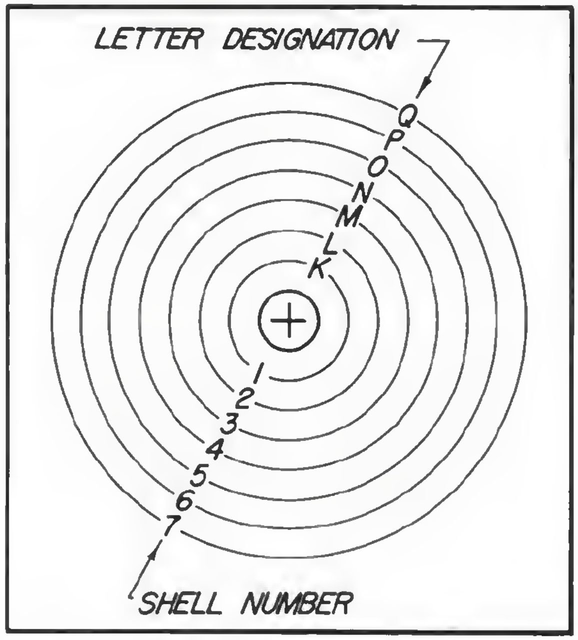

Figure 1-8 - Shell designation.

and progressing outward, the shells are labeled K, L, M, N, O, P, and Q respectively. The shells are considered to be full or complete when they contain the following quantities of electrons: two in the K shell, eight in the L shell, eighteen in the M shell, and so on in accordance with the exclusion principle. Each of these shells is a major shell and can be divided into subshells of which there are four labeled s, p, d, and f. Like the major shells, the subshells are also limited as to the number of electrons which they can contain. Thus, the s subshell is complete when it contains two electrons, the p subshell when it contains six, the d subshell when it contains ten, and the last subshell when it contains fourteen electrons.

Inasmuch as the K shell can contain no more than two electrons, it must have only one subshell, the s subshell. The M shell is composed of three subshells: s, p, and d. If the electrons in the s, p, and d subshells are added, their total is found to be eighteen the exact number required to fill the M shell. This relationship exists between the shells and subshells up to and including the N shell. Beyond the N shell, the actual number of electrons required to fill a shell has not been experimentally determined. Notice the difference between the electron configurations for copper and sodium illustrated in Figure 1-9.

Q13. How many electrons are found in the last subshell of an aluminum atom?

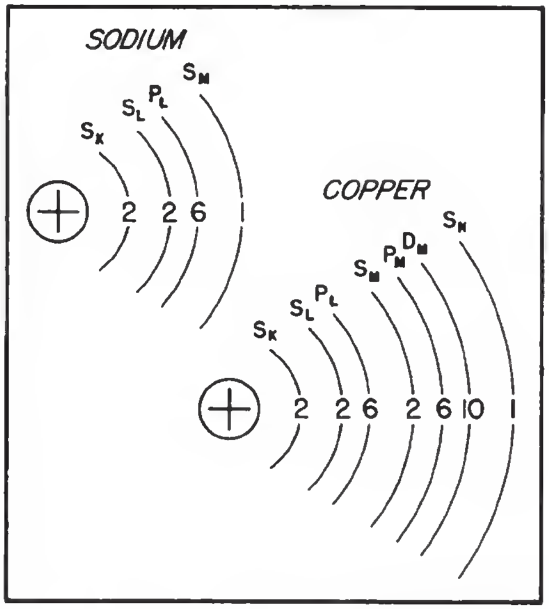

Figure 1-9 - Copper and sodium atoms.

Q14. What force could act on an electron for an electron to move from the K shell to the M shell?

1-24. Atomic Weight and Atomic Number

There are a wide variety of atoms, a different type of atom comprising each of the 102 known elements. Each atom is similar in that all atoms consist of protons and electrons. However, atoms of different elements contain varying numbers of basic particles, thus causing a difference in weight. A classification, based on the ATOMIC WEIGHT AND ATOMIC NUMBER of the atoms has been devised to differentiate between different atoms.

Although atoms are far too small to be weighed, a system has been set up whereby the weight of one atom is given with reference to a universally accepted standard. This system of weights, called the atomic weight of the elements, uses the element oxygen as a reference. The atomic weight of oxygen is assigned a numerical value of sixteen, and the atomic weights of other elements are determined by comparison with oxygen. No element will have an atomic weight less than one. The lightest element known, hydrogen, has an atomic weight equal to 1. 0008. The atomic weight of the atoms of different elements is found in the periodic table. (See Volume 8.)

As previously stated, the proton and the neutron have the same mass. If the mass of a proton represents an atomic weight of one, the mass of an electron (1/1845 that of a proton) is negligible. The mass of an atom would therefore be governed by the weights of the protons and neutrons. An element such as the gas helium, with an atomic weight of 4. 003, obtains its mass from two protons and two neutrons in its nucleus.

Included in the periodic table along with the atomic weight is another system of classifying the elements called the atomic number. The atomic number is the number of protons found in the nucleus, therefore, it also indicates the number of electrons associated with the atom. Atoms in their natural state have an equal number of electrons and protons.

Notice in the periodic table the significance of the atomic weights and the atomic numbers. In each of the periods, the elements are separated by atomic weight and atomic number. If one reads the periods from left to right, the atomic weight and the atomic numbers increase in magnitude. This periodic recurrence is the reason this table is called a periodic table.

Q15. The element magnesium has an atomic number of 12. How many electrons are contained in the atom?

Q16. The element magnesium has an atomic weight of 24. 32. Describe the particles that contribute to its mass.

Q17. A heavier element such as gold has an atomic weight of 197 and an atomic number of only 79. If particles such as electrons, nutrinos, and mesons contain a mass of negligible amount, what particle must contribute the greatest amount of mass to this element?

1-25. Valence

The number of electrons in the outer most shell, less than the full permissible complement for that shell, determines the VALENCE of the atom. For this reason, the outer shell of an atom is called the VALENCE SHELL; and the electrons contained in this shell are called the valence electrons. The valence of an atom determines its ability to gain or lose an electron, which in turn determines the chemical and electrical properties of the atom. An atom that is lacking only one or two electrons from its outer shell will easily gain electrons to complete its shell, but a large amount of energy is required to free any of its electrons. An atom having a relatively small number of electrons in its outer shell in comparison to the number of electrons required to fill the shell

A13. One.

A14. Heat, light, or electrical energy.

A15. Twelve electrons.

A16. Twelve protons and twelve neutrons contribute to most of the mass. Additional sub-atomic particles contribute the fractional part.

A17. The neutron.

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will easily lose the valence electrons.

The valence shell always refers to the outer most shell, whether it be a major shell or a subshell. The copper and sodium atoms each have one electron in the outer most shell. Even though the atomic weights and atomic numbers of copper and sodium are quite different, the atoms are similar in that they both contain one valence electron. Since copper (cu) and sodium (Na) have one valence electron, they both appear in group one of the periodic table. Group one designates all elements having one valence electron.

Q18. When sodium enters into a chemical reaction, is it more likely to lose an electron or gain an electron?

1-26. Ions and Ionization

It was mentioned previously that ions do exist and that they are atoms that have assumed a charge. It was stated that there are positive and negative ions. The process whereby an atom acquires a charge will not be discussed.

It is possible to drive one or more electrons out of any of the shells surrounding the nucleus. In the case of incomplete shells, it is also possible to cause one or more additional electrons to become attached to the atom. In either case, whether the atom loses electrons or gains electrons, it is said to be IONIZED. For ionization to take place there must be a transfer of energy which results in a change in the internal energy of the atom. An atom having more than its normal amount of electrons acquires a negative charge, and is called a NEGATIVE ION. The atom that gives up some of its normal electrons is left with less negative charges than positive charges and is called a POSITIVE ION. Thus, ionization is the process by which an atom losses or gains electrons.

To drive electrons out of the shells of an atom requires the internal energy of the atom to be raised. This energy may be obtained through bombardment by photons and phonons or by subjecting the atom to electric fields. The amount of energy required to free electrons from an individual atom is called the ionization potential.

The ionization potential necessary to free an electron from an inner shell is much greater than that required to free an electron from an outer shell. Also, more energy is required to remove an electron from a complete shell than an unfilled shell.

Q19. When light is produced by ionization does the light occur when the electron jumps from an outer shell to an inner shell, or from an inner shell to an outer shell?

CRYSTAL STRUCTURE

1-27. The Crystal Lattice

Now that all matter has been shown to consist of a fundamental unit called an atom, the arrangement of the atoms within a material may be investigated. Practically all of the inorganic (non-living) solids occur in CRYSTALLINE form. A single crystal of carbon is the precious stone known as a diamond. Even materials like iron, copper, and aluminum are crystalline in nature. A piece of iron is made of a great number of crystals lying in random positions throughout the material. A substance composed of a large number of crystals is called a POLYCRYSTALLINE material.

If one were to examine common table salt under a magnifying glass the small grains would appear as tiny cubes of salt. Each of these cubes has a precise atomic structure and constitutes a single crystal of salt. The arrangement of atoms in a salt (sodium chloride) crystal is shown in Figure 1-10. In a salt crystal the atoms become ionized as the crystal is formed. The lines between the ions of sodium and chloride represent the chemical bonds which hold the crystal together. Due to the way in which the bonds form, every perfect crystal will be like every other crystal. This precise repeating arrangement of atoms within a crystal is called a crystal LATTICE. The physical properties of a material (hardness, tensile strength, etc.) are to a great degree dependent upon the lattice structure of the material.

Q20. Could a liquid have a lattice structure? Explain.

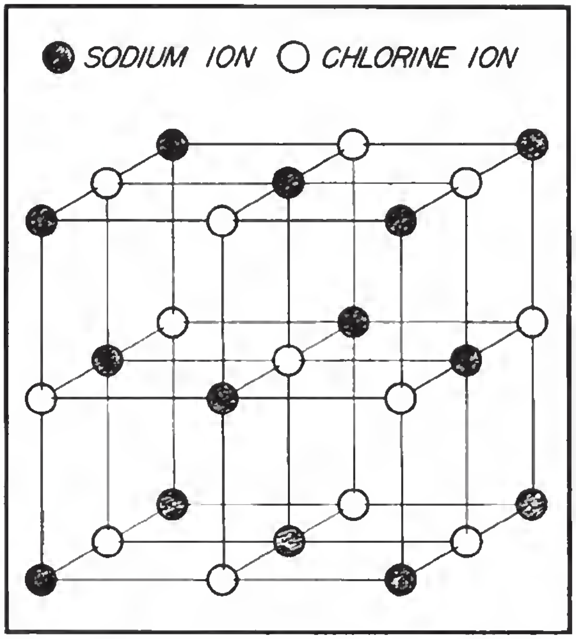

Figure 1-10 - Atomic lattice structure of salt.

1-28. Conductors, Semiconductors, and Insulators

In the study of electronics, the association of matter and electricity is of paramount importance. Since every electronic device is constructed of parts made from ordinary matter, the effects of electricity on matter must be well understood. As a means of accomplishing this, all the elements of which matter is made may be placed into one of three categories: CONDUCTORS, SEMICONDUCTORS, and INSULATORS. Conductors for example, are elements such as copper and silver which will conduct a flow of electricity very readily. Due to their good conducting abilities they are formed into wire and used whenever it is desired to transfer electrical energy from one point to another. Insulators (non-conductors) on the other hand, do not conduct electricity to any great degree and are therefore used when it is desirable to prevent a flow of electricity. Elements and compounds such as sulphur, rubber, and glass are good insulators. Materials such as germanium and silicon are not good conductors but cannot be used as insulators either, since their electrical characteristics fall between those of conductors and insulators. These in-between materials which do not make good conductors, or good insulators are classified as semiconductors.

The electrical conductivity of matter is ultimately dependent upon the energy levels of the atoms of which the material is constructed. In any solid material such as copper, the atoms which make up the molecular structure are bound together in the crystal lattice. Since the atoms of copper are firmly fixed in position within the lattice structure, they are not free to migrate through the material, and therefore cannot carry the electricity through the conductor.

1-29. Free Electrons

In section 1-26 it was found that by the process of ionization, electrons could be removed from the influence of the parent atom. These electrons, once removed from the atom, are capable of moving through the copper lattice under the influence of external forces. It is by virtue of the movement of these charged electrons that electrical energy is transported from place to place.

The ability of a material such as copper to conduct electricity must therefore depend on the number of dislodged electrons normally available within the lattice. Since copper is a good conductor, it must contain vast numbers of dislodged or FREE electrons.

To understand how the electrons become free, it is necessary to refer back to the electron energy levels within the atom. It was previously stated that if precisely the right amount of energy was added to an orbital electron, it would jump to a new orbit located farther from the nucleus. If the energy is sufficiently large, the jump may carry the electron to such a distance from the positive nucleus that the electron becomes free. Once free, the electron constitutes the charge carrier discussed above. The only problem remaining is to determine how the electron in the piece of copper obtains enough energy to become free.

After a moments consideration a person realizes that the average piece of copper contains some amount of heat energy. In fact, a piece of copper at room temperature (72°F) is approximately 531°F above absolute zero! This temperature indicates that the copper, although only warm to the touch, must contain a considerable amount of heat energy. The phonons of heat energy, along with other forms of natural radiation, elevate the electrons to the energy levels where they can become free.

1-30. Energy Gaps

From the preceding theories, one might wonder why all materials containing the same amount of heat energy do not conduct electricity equally well. The answer lies in the fact that the electrons in various materials require different amounts of energy to become free. This idea may be best developed by using energy level diagrams like the one in Figure 1-11. In

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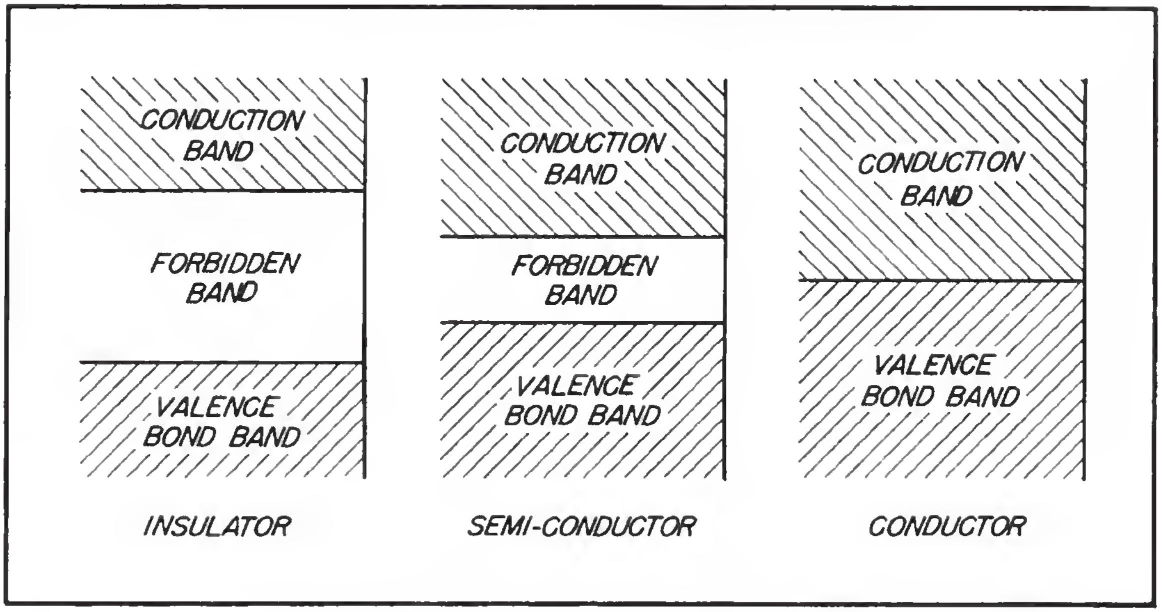

Figure 1-11 - Energy level diagrams.

A18. Lose an electron.

A19. Outer shell to inner shell.

A20. No. A lattice structure only exists in a solid.

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this model, the outer shell is depicted as having two energy bands called the valence band and the conduction band. Between these two energy bands is an energy gap called the forbidden gap or forbidden band. Electrons residing in the lower band are considered to be firmly attached to the parent atoms and are not available for the conduction of electricity. In order for an electron to become a free electron, it must gain enough energy from external forces to jump the forbidden gap and appear in the conduction band. Once in the conduction band, the electron is free and may be made to move along through the conductor in the form of an electric current. The energy diagram for the insulator shows the insulator to have a very wide energy gap. This means that a large amount of energy must be added to each electron in an insulating material before it can become free. Thus at room temperature sufficient energy is not available to cause electrons to jump to the conduction band and the material has practically no free electrons. In comparing the energy level diagrams for an insulator and a conductor, the conductor is seen to have little or no forbidden gap. Since this is true, under normal conditions the conduction band for a conductor contains a sufficient number of electrons to make it a good conductor of electricity.

The semiconductor being neither a good conductor or a good insulator has a gap energy between that of a conductor and that of an insulator.

In the following chapters the role of the conductor, semiconductor, and insulator will assume larger and larger importance as the various electronic devices are developed and discussed. In fact, in the final analysis, all electronic phenomena are based on the electrical nature of matter.

EXERCISE 1

1. What property of matter gives it inertia?
2. What are the three states of matter?
3. What is the name of the process whereby a material goes from one state to another without passing through the intermediate state?
4. What are the units used to measure pressure?
5. Give an example of discontinuous matter and compare the idea of discontinuous matter to continuous matter.
6. What are packets of light energy called?
7. What are packets of heat energy called?
8. Define and give an example of an element.
9. Rubidium is in which group and period of the periodic table?
10. What name is given to elements 95 through 102?
11. Give three examples of metals, non-metals, and gases.
12. Define and give an example of a compound.
13. Define and give an example of a solution.
14. What is meant by the term homogeneous solution?
15. Give an example of a heterogenous solution.
16. Define and give an example of a molecule.
17. Give an example of a diatomic molecule.
18. Define the term chemical change.
19. State two of Dalton's postulates concerning the structure of an atom.
20. What is meant by the term charge?
21. Describe three properties of an electron.
22. What is a proton?
23. What is a neutron?
24. What is the relationship between the mass of a proton and neutron?
25. Describe the nucleus and its basic contents.
26. What are the disadvantages of Thompson's atomic model?
27. Through what experiment was the idea of a miniature solar system applied to the atom? What scientist was responsible?
28. Define centripetal and centrifugal force.
29. Describe Bohr's idea concerning the structure of the hydrogen atom.
30. What are shells? Subshells?
31. Define atomic number and atomic weight.
32. What is a "free" electron?
33. Explain what is meant by the term "single crystal."
34. Explain what is meant by the term "polycrystalline."
35. What is a "crystal lattice?"
36. Compare the difference between conductors, semiconductors, and insulators using as a measure, the width of the energy gap and the number of mobile electrons.
37. Define ionization and give examples of positive and negative ions.

CHAPTER 2

ELECTROSTATICS

The study of electrostatics should be very interesting. It is a subject with which most persons entering the field of electronics are somewhat familiar. For example, the sparks created by touching an object after walking across a deep-piled rug; the way a person's hair stands on end after a vigorous rubbing;and the flash of lightning during a thunderstorm; these are all effects of electrostatics. While pursuing the study of electrostatics, one should gain a better understanding of these common occurrences. Of even greater significance is the opportunity to gain important background knowledge and to develop concepts which are essential to the understanding of electricity and electronics.

In the study of electrostatics it will be necessary to deal with several mathematical equations called formulas. To properly use these formulas, the student must be familiar with scientific notation, and ratio and proportion. These two subjects are discussed in detail in Volume 8, MATHEMATICAL OPERATIONS.

HISTORY OF ELECTROSTATICS

2-1. Historical Development

Interest in the subject of electrostatics can be traced back to the ancient Greeks. The Greek philosophers, primarily interested in the makeup of the world, were concerned about lightning, one of the effects of electrostatics. This interest in the wonders of nature was to lead to the development of the science of electrostatics.

Thales of Miletus, a Greek philosopher and mathematician, is credited with the start of electrostatics as a scientific study. About the year 600 B.C., Thales discovered that an amber rod, when rubbed with fur, had the amazing characteristics of attracting some very light objects such as bits of paper and shavings of wood. This discovery had little scientific effect at this time but soon led to amusing parlor games whereby many guests were entertained by this mysterious property of amber.

Little more was done about Thales' scientific discovery until about 1600 when William Gilbert, an English scientist, made a study of other substances which had been found to possess qualities of attraction similar to amber. Among the other substances which had characteristics similar to amber when brought near light non-metallic objects were: glass when rubbed with silk, and ebonite when rubbed with fur. Gilbert, attempting to find out more about this strange force, classified all the substances which possessed properties similar to those of amber as electrics. Substances not possessing properties of amber were considered non-electrics. This classification is not acceptable today. Gilbert's work gave much needed knowledge and also the everyday term electric, a Greek derived word meaning amber.

Due to Gilbert's work with electrics, a substance such as amber or glass when given a vigorous rubbing is considered to be electrified or charged with electricity.

In the year 1733, Dufay made an important discovery about electrification. He found that when a glass rod was rubbed with cat's fur both the glass rod and the fur became electrified. The realization of this came when he systematically placed the glass rod and the fur near other electrified substances and found some substances that were attracted to the glass rod were repelled by the fur and vice versa. From experiments such as this, he concluded that there must be two exactly opposite kinds of electricity.

Benjamin Franklin, who started working with electricity about the year 1746, is credited with first using the terms POSITIVE and NEGATIVE to describe the two opposite kinds of electricity. The type of electricity produced on a glass rod when it is rubbed with silk, Franklin labeled positive. He attached the term negative to the opposite type of electricity produced on the silk. Franklin used these terms, positive and negative as a means to distinguish between the two opposite kinds of electricity. To those bodies which were not electrified or charged, he gave the name NEUTRAL bodies.

The experiments of these early scientists proved very important to scientific progress throughout the world. Their studies of static electricity led to the development of our present electron theory of matter which has been highly successful in explaining electrical behavior.

With the electron theory, many questions concerning the phenomenon of static electricity can now be answered.

NATURE OF CHARGES

2-2. Determination of Charge

Before any electric attraction or repulsion can take place between two bodies, the bodies acquire an electric charge. To understand what occurs when a body becomes charged, it is necessary to consider atomic structure and the electron theory of matter.

From the study of atomic structure it was found that each atom of matter, when in its natural or neutral state, had the proper number of electrons in orbit around its nucleus. The required number of electrons which make up the atom is the same as the number of protons in the nucleus. Because of an equal number of electrons and protons, the net negative charge of the electrons balances the net positive charge of the nucleus thereby making the atom electrically neutral.

It will be recalled from section 1-26 that whenever the internal energy of the atom is raised far enough above its normal state, one or more of its electrons makes use of this added energy and frees itself from its parent atom. The atom which has given up the electron has more protons than electrons and is now considered a positive ion or a positively charged particle. Besides giving up electrons, the atom has the ability to gain an electron that has been given up by another atom. With an added electron, there is a greater number of electrons than protons, therefore the atom acquiring the electron becomes a negative ion or a negatively charged particle.

If a material could be composed entirely of neutral atoms the net charge would be neutral. When some ions are mixed with the neutral atoms, the predominant charge of the ions will be the overall charge of the entire body.

Due to various types of natural energy such as light and heat constantly reacting on atoms of all substances, some ions are always present. These ions determine the electric charge of the material. If there is a like number of positive and negative ions, equally charged, their opposite charges balance each other just as did the charge of the protons and electrons in normal atoms. As a result of this, the substance has a net charge of zero and is referred to as being a neutral body of matter. When there is a greater number of positive ions in comparison to the negative ions there is a deficiency of electrons, therefore the body has a positive charge. However, if the negative ions are predominant, the body will have a negative charge. Since ions are actually atoms without their normal number of electrons, it is ultimately a substance's excess or deficiency of electrons that determine its charge. In most solids the transfer of charge is by movement of electrons rather than a transfer of ions. In liquids and gases, the transfer of charges by ions is very common.

Q1. Why would the transfer of charge in a solid consist of a movement of electrons rather than a movement of ions?

2-3. Law of Charged Bodies

Now that you have a better understanding of charged bodies, an experiment showing the LAW OF CHARGED BODIES will be illustrated. This law of charged bodies is a fundamental law of electricity and indicates the effect of the electric force between charged bodies.

LAW 1 - Like charges repel each other, unlike charges attract.

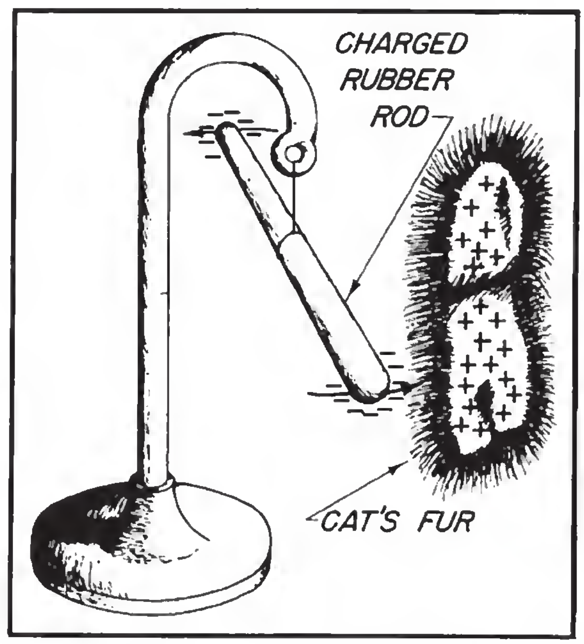

Figure 2-1 - Unlike charges attract.

The law is proven by the following: A rubber rod is suspended so that it has freedom of movement as shown in Figure 2-1. A negative charge is placed on the end of this rod by rubbing it vigorously with cat's fur. Since a negative charge is placed on the rod, the fur is left

A1. The ions (charged atoms) in a solid are firmly bound to each neighboring atom and are not free to move as are the electrons.

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with a positive charge.

These two bodies now possess opposite charges. As the positively charged fur is brought close to the negatively charged rod, the rod will move toward the fur. This shows that a force of attraction exists between oppositely charged bodies.

Restore the negative charge on the suspended rubber rod by rubbing it with the cat's fur. Also similarly charge a second rubber rod so that the suspended rubber rod and the second rod both possess negative charges. As the like charged bodies approach each other, the suspended negatively charged rod swings away from the other negatively charged rod (see Figure 2-2). This same repelling effect could also be illustrated with two positively charged bodies. All like charged bodies will repel one another, whether the like charges are positive or negative.

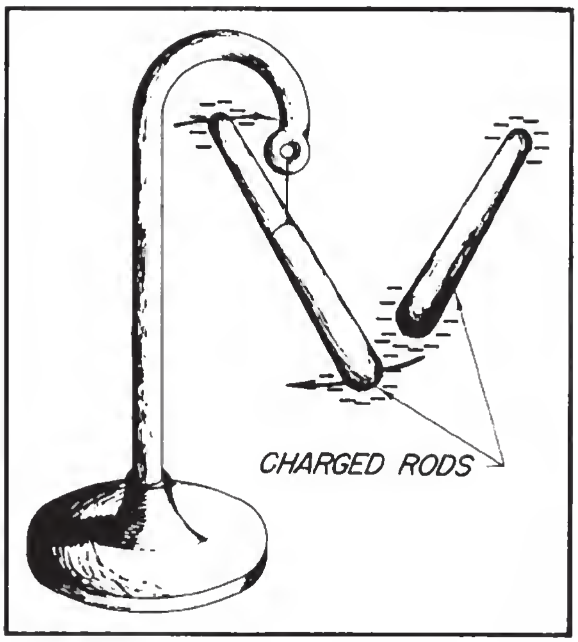

Figure 2-2 - Like charges repel.

Q2. A substance is composed of five million atoms and eight thousand ions. Exactly half of these ions are particles of matter with equal positive charges. Describe the charge on the remaining particles of matter necessary for the substance to be a neutral body.

Q3. Assume that the positive ions of the above question are now atoms with a deficiency of three electrons. If the remaining ions were atoms with an excess of two electrons, what polarity is the charge of the substance?

Q4. Upon what does the charge on a body depend?

METHODS OF CHARGING

2-4. Charging by Friction

One of the easiest means of creating a charge is by the friction method. The charge placed on the rubber rod in the previous experiment was due to the heat created between the rod and the fur by rubbing. The heat produced by friction increased the energy level of many electrons in the fur thus permitting them to be easily transferred onto the rod. Additional energy was supplied to the electrons contained in both materials, but because of the difference in atomic structure the effect of this added energy is that many electrons are transferred from the fur to the rod. Transfer of charges will not go on indefinitely. As the rubber rod accumulates electrons, a negative field is built up about the rod which retards the transfer of additional electrons from the fur to the rod. Eventually, the rod becomes sufficiently negative to repel any additional electrons which are removed from the fur. While this action takes place, the fur assumes a positive charge and tends to attract back its liberated electrons. This also helps to limit the number of electrons which may be transferred.

If it is desired to create a detectable static charge by the friction method, it is advantageous to use two different non-conductors. The rubber rod when rubbed with fur obtains a negative charge which does not escape readily because rubber is an insulator. When materials are used which are good conductors, it is quite difficult to detect a charge on either body. For example, if a copper rod is rubbed with silk it becomes charged. However, if we are holding the copper rod in our hand the charge will rapidly conduct away through our body which is also a fair conductor. The reason for this is that electrons will easily move through the conducting materials thereby equalizing the charges almost as fast as they are created. A static charge is easiest to obtain by rubbing a hard non-conducting material against a soft, or fluffy non-conductor.

Q5. Explain what happens in the process of combing your hair that would cause a rubber comb to pick up bits of paper.

Q6. Explain what would happen in question number five if the comb were made of metal.

2-5. Charging by Contact

A charged body such as a rubber rod can transmit some of its charge to other bodies by contact with those bodies. If the rubber rod (negatively charged) is brought in contact with a neutral body as shown in Figure 2-3, some electrons will flow to the neutral body. The neutral body having taken on a greater number of electrons now becomes negatively charged.

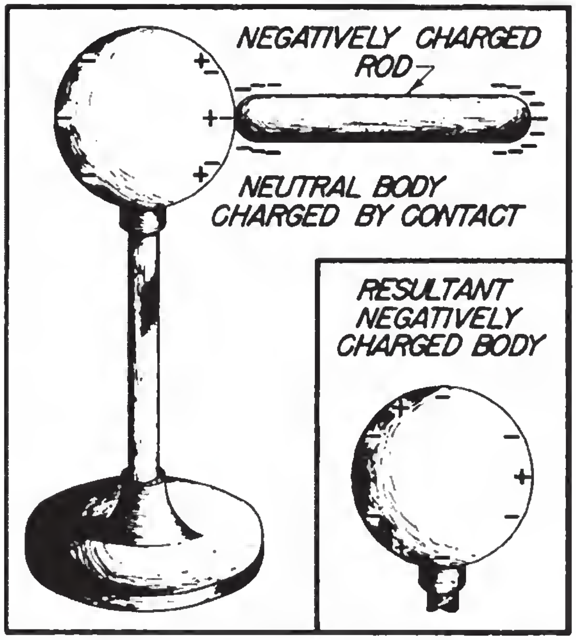

Figure 2-3 - Charging by contact

The cause of this transfer of electrons between bodies reflects back to Law 1, The Law of Charged Bodies. The neutral body has an equal number of positive and negative charges. In contrast the charged body has an excess of electrons. Since like charges repel one another each excess electron on the charged body is repelled by every other electron it contains. When the charged body is brought in contact with the neutral body, some of the excess electrons are repelled or forced from the charged body to the neutral body.

When the negatively charged body is removed (Figure 2-3), the body that had been neutral now has acquired an excess of electrons and is negatively charged. In all cases of charging by contact, the body to be charged always takes on the same kind of charge as the body giving it the charge.

Q7. If a body with a deficiency of electrons is brought in contact with a neutral body, explain what takes place.

2-6. Charging by Induction

Another means of placing a charge on a body is through a process called induction. If a neutral body is suspended as shown in Figure 2-4, and a charged body is brought near but not in contact with the neutral body, charging by induction can be demonstrated.

If a negatively charged rubber rod is brought near a neutral body (a copper bar), the excess electrons which have accumulated on the surface of the rod repel electrons of the copper toward the end opposite that of the charged body. There is now an accumulation of electrons at one end of the copper bar for as long as the charged body continues to be held nearby. Though electrons become bunched together at the end of the bar, the total charge throughout the material remains unchanged.

If the copper bar is now placed in contact with a much larger neutral body, such as the earth, the electrons which are being repelled along the copper bar are now transferred to

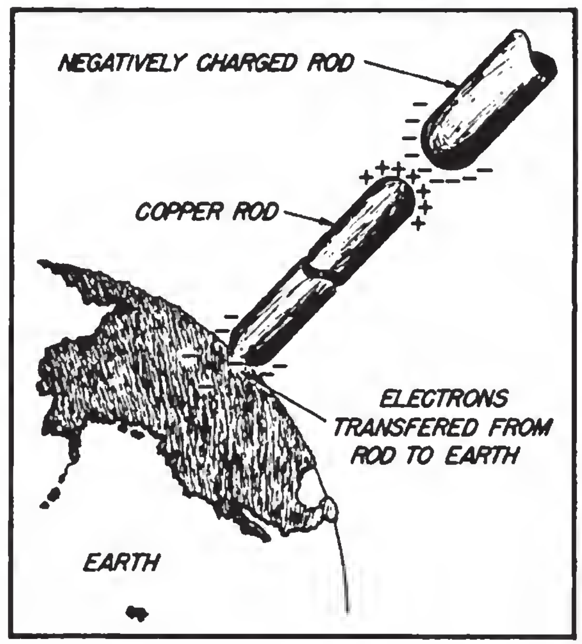

Figure 2-4 - Charging by induction

the larger neutral body. This transfer of electrons takes place until there is an equalization between their charges or until the contact between the bodies is broken. Equalization occurs when the force of repulsion from the negative rubber rod is exactly counterbalanced by the positive force of attraction resulting from the positive charges generated at the unearthed end of the

A2. The remaining four thousand ions would possess equally negative charges.

A3. Positive.

A4. Charge is dependent on a body's excess or deficiency of electrons.

A5. The rubber comb becomes charged by friction.

A6. No detectable charge. Charge is conducted away through one's body.

A7. Electrons will pass from the neutral body to the positive body in an attempt to balance the electron deficiency.

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copper bar.

You might wonder how there could be a movement of electrons from one neutral body to another. This question is answered by the fact that there are no perfectly neutral bodies. All bodies have at least some minute charge. However, when these charges are not detectable, we can consider these bodies to be neutral.

In the instance when the neutral rod made contact with the earth, electrons were repelled to the earth by the electrostatic force from the negatively charged rubber rod. Although many electrons were repelled to the earth, it is still considered to be neutral. This is permissible because of the vast quantity of electrons that would be necessary to appreciably change the earth's charge. Due to the electrons being repelled to the earth from the neutral copper bar, the copper is left lacking electrons and acquires a detectable positive charge. Keep in mind the important fact that the negatively charged rubber rod was near but not in contact with the copper bar; therefore, no electrons were transferred from the rod to the copper bar. In all cases of electrostatic induction, the body being charged will acquire a charge opposite to that of the charging body.

Q8. What would occur if the copper bar in Figure 2-4 were replaced with a glass bar?

Q9. Explain the charging process as occurring in Figure 2-4 when the negatively charged rod is replaced with a positively charged glass rod.

2-7. Attraction of Neutral Bodies

With a firm understanding of the behavior of charged bodies, the attracting properties of the amber rod, which mystified the ancient Greeks can now be investigated. It will be recalled that an amber rod, when charged, has the ability to pick up light objects. Bear in mind that these light objects that were attracted to the amber were uncharged or neutral bodies.

To obtain a better understanding of this phenomenon, a demonstration can be performed with a pith ball and a charged rod. This tiny ball is cut from the pithy core of a corn cob and coated with tin foil or metallic paint. When the charged rod is brought near the ball as in Figure 2-5, free electrons on the ball (a neutral body) are repelled to the far side by the negatively charged rod thereby leaving a positive charge on the side nearest the rod. The total charge on the pith ball remains unchanged, but the one side of the ball is left with a deficiency of electrons and therefore is attracted momentarily to the rod. When contact is made, electrons flow from the rod to the ball neutralizing the nearby positive charges and increasing the total number of electrons on the ball. The total charge of the ball now becomes negative, and it moves away from the negatively charged rod due to mutual repulsion.

The experiment wherein the charged amber rod is used to pick up bits of paper is similar in principle to the one just illustrated with the pith ball. Due to the electrostatic force from the charged amber rod, there is a pronounced shifting of electrons on the paper. This creates a bound induced charge (no change in net charge) on the bits of paper. Attraction occurs because the area of the paper nearest the charged rod possesses an opposite charge. As a result of charging by contact, a transfer of electrons occurs between the bodies. However, due to the insulating properties of the paper the transfer of electrons from the rod to the paper would progress at a very slow rate, and an immediate repelling effect will not be observed.

LOCATION OF CHARGES

2-8. Non-Conductors

Static charges that are acquired by a non-conductor such as hard rubber, glass, or amber, will remain at about the same position on the object as where they first originate. Therefore, most of the charges on a non-conductor will be felt on specific areas of its surface.

2-9. Conductors

When a conductor such as silver or copper acquires a charge, the charge will quickly spread over the exterior of the conductor. In the case of a metallic sphere the charge will spread itself uniformly over its entire surface. With an object having an irregular curvature, the distribution of the charges will not reflect

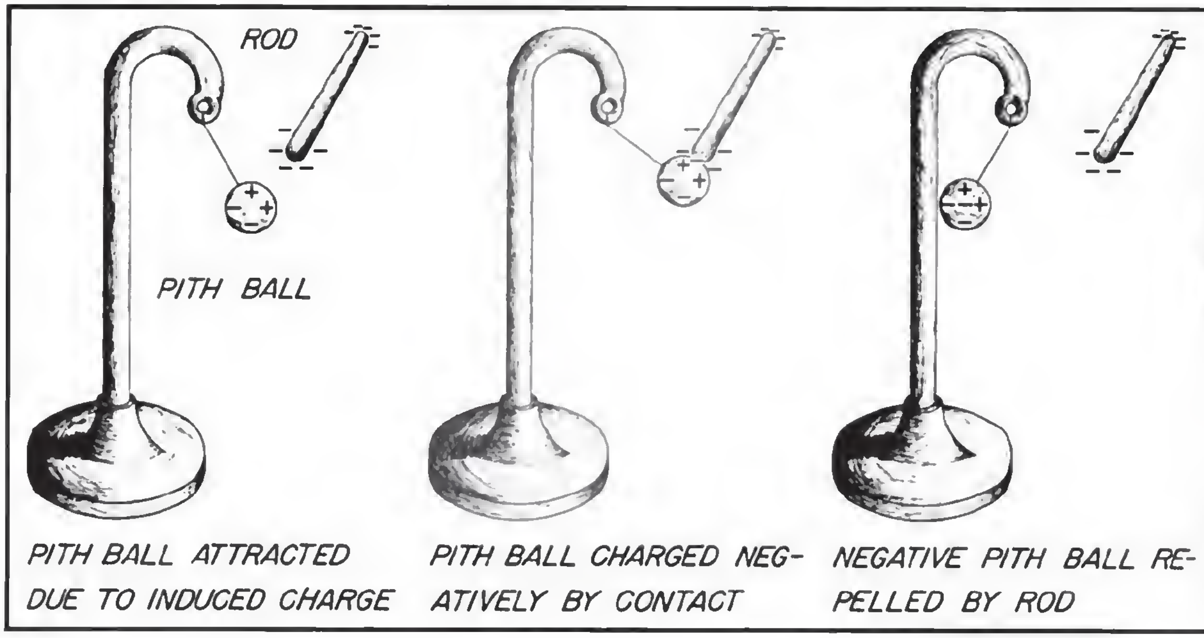

Figure 2-5 - Pith ball experiment

the same uniformity but will show some fixed pattern.

It has been found by Michael Faraday and others that the greatest quantity of charges will always accumulate on the area of an object which possesses the sharpest curvature. Examination of the charges on the various shaped objects in Figure 2-6 will give some idea of this concept. The drawings indicate negative charges, but positive charges would accumulate in the same pattern.

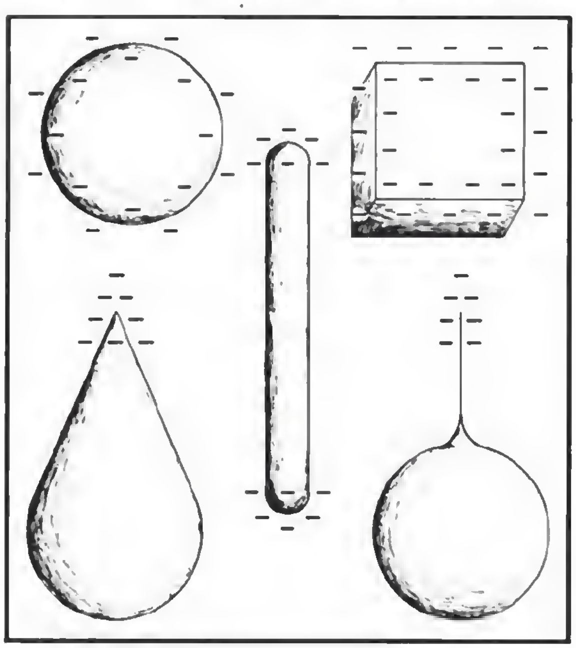

Figure 2-6 - Location of charge

It was also proven by Faraday that no charge could exist inside a hollow conductor and that all charges whether on a hollow or solid conductor appear on the outer surface.

The use of this knowledge pertaining to location of charge becomes apparent if we think about the design of lightning rods, or the design of an electrode in a spark plug. An understanding of these devices will be better realized when the study of static discharging is completed.

MEASUREMENT OF CHARGE

2-10. The Electroscope

The detection of a charge on a body is often accomplished by observing the charged body's ability to attract other light bodies. This system of detection is not considered sensitive enough for practical use in scientific study.

An instrument capable of measuring the existing charge and also useful in the study of electrostatic phenomena is the electroscope. One form of this device consists of two thin gold leaves attached to a metallic rod, the other end of which is terminated by a small sphere. These leaves are usually enclosed in a glass walled container to insure that they are not adversely effected by air currents. The

A8. No charge would result. Electrons could not easily flow through the insulated glass bar.

A9. Electrons would be attracted from, rather than repelled to the earth. Bar charges negatively.

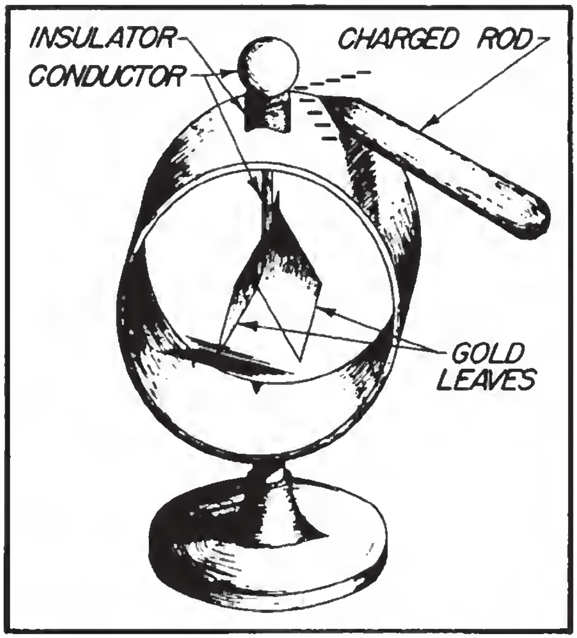

Figure 2-7 - The electroscope.

sensitivity of the device will be determined primarily by the thickness and type of material used for the leaves. An example of the electroscope is shown in Figure 2-7.

If an object containing a charge is brought near the terminal of an electroscope, the two leaves will diverge. This spreading apart of the leaves occurs as a result of the repelling effect existing between the like charges that are forced on to the two leaves by the charged object. The greater the charge, the greater will be the mutual repulsion between the leaves. When using a sensitive electroscope, the charge on the leaves should be felt through induction, otherwise the leaves may be ripped from the device due to the great repelling force of the similarly charged leaves. However, charging by contact with the metallic sphere may be necessary in the case of less sensitive devices.

Q10. What two electrostatic principles are illustrated by the operation of the electroscope?

Q11. List three factors which determine how far the leaves of an electroscope will spread under the influence of a charged object.

2-11. Coulomb's Law

Much has been said pertaining to charged bodies and what effect they have on one another. Although it was established that like charges repel and unlike charges attract, nothing has been mentioned concerning the magnitude of this electrostatic force.

About the year 1780, Charles Coulomb discovered the relationship of charge and distance to electrostatic force. His findings later became what is known as Coulomb's Law, stated here as Law 2.

LAW 2. The force between two charges is directly proportional to the product of the charges and inversely proportional to the square of the distance between the charges.

This is expressed mathematically as:

$$F = \frac{Q_1 Q_2}{Kd^2} \qquad (2\text{-}1)$$

where: F = force in dynes

Q_1 = strength of charge 1 in electrostatic units (e. s. u.)

Q_2 = strength of charge 2 in electrostatic units

d = distance separating charges in cm.

K = dielectric constant of the medium through which the force is exerted.

The mathematical expression makes use of literal numbers which have already been described as letters or symbols used to represent known or unknown quantities. The subscripts 1 and 2 on the letter Q simply indicate that two different charges are involved. The letters in this particular expression stand for quantities which must be measured in some specific unit. Formula (2-1) utilizes the cgs system of measurement previously introduced in section 1-2. An application of its units of measurement will now be considered.

Since Coulomb's Law considers force between bodies, an investigation of the definition of force used in physics is necessary at this time. By this definition, force is: "the cause

of the acceleration of movement of material bodies." The force which causes a body to fall freely in our planetary system is known as weight, a force exerted by gravity. In the English system of measurement, this mechanical force of gravity is measured in a specific unit, the pound.

The movement of a physical body can be accomplished by a mechanical force, but as was illustrated in Figure 2-1, and 2-2, movement of bodies can also be produced by an electrical force. It is this electrical force that is considered in Coulomb's Law. This force also needs some basic unit and in the cgs system of measurement, the unit of electrical force is the dyne.

In addition to a unit of force, Coulomb's Law requires a basic unit of charge. The unit used is the electrostatic unit (e. s. u.) often called a statcoulomb. One electrostatic unit is defined as: "that charge which when placed one centimeter from an equivalent charge exerts on it a force of one dyne." (Refer to Figure 2-8).

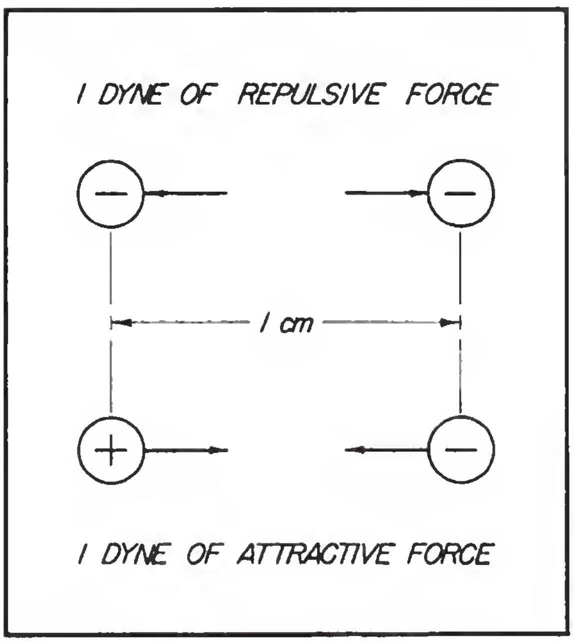

Figure 2-8 - The electrostatic unit

The centimeter, defined previously, is a measure of distance in the metric system. These units of measure and others of the metric system are used throughout the study of physical science.

Looking back at Coulomb's Law, a sample problem will help to emphasize his findings.

Example 2-1. What force is exerted between two positive charges of 20 and 40 electrostatic units respectively when placed two centimeters apart?

Given: $Q_1 = 20$ e. s. u.

$Q_2 = 40$ e. s. u.

$d = 2$ cm.

$K = 1$

Find F:

Solution:

$$F = \frac{Q_1 Q_2}{Kd^2}$$

$$F = \frac{20 \times 40}{1 \times (2)^2}$$

$$F = \frac{800}{4}$$

$F = 200$ dynes of repulsion

NOTE: The dielectric is the insulating medium through which the electric force is penetrating, and the dielectric constant (K) expresses the electrical characteristics of this material. A vacuum is the standard used for reference and is assigned a numerical dielectric constant of one. The dielectric constant of air is 1. 0006, so close to that of a vacuum that it too is considered to have a dielectric constant of 1. Any problem in which a dielectric is not mentioned considers air to be the dielectric.

This mathematical expression states that force is directly proportional to the product of the charges. If the value of either charge is increased, the force between the charges will increase proportionally.

Example.2-2. Refer to the problem of the previous example. Double the charge of Q_1 and allow the other unit values to remain unchanged.

Given: $Q_1 = 40$ e. s. u.

$Q_2 = 40$ e. s. u.

$d = 2$ cm.

$K = 1$

Find F:

Solution:

$$F = \frac{Q_1 Q_2}{Kd^2}$$

$$F = \frac{40 \times 40}{1 \times (2)^2} = \frac{1600}{4}$$

$F = 400$ dynes of repulsion

A10. (a) Charging by induction, (b) law of charged bodies.

A11. (a) Magnitude of charge, (b) spacing between charge and electroscope, (c) composition of leaves.

From the example, it can be seen that as the value of one of the charges is doubled the force of repulsion between the charged bodies is also doubled. If these had been oppositely charged bodies, the force of ATTRACTION would have doubled. The equation for oppositely charged bodies could be expressed as follows:

$$F = \frac{-(Q_1Q_2)}{Kd^2} \quad \text{or:} \quad F = \frac{Q_1(-Q_2)}{Kd^2}$$

The resultant force expressed in dynes would bear a negative sign which would indicate that the bodies were oppositely charged and the force between them would be attraction instead of repulsion. Referring to the direct proportionality between the value of charge and force; if the product of the charges is halved, the force between the charged bodies will also be halved.

Example 2-3. If we take the same values of charges as given in Example 2-1 and double the distance between the charges from 2 centimeters to 4 centimeters, what is the force between the charges?

Given: $Q_1 = 20$ e. s. u.

$Q_2 = 40$ e. s. u.

$d = 4$ cm.

$K = 1$

Find F:

Solution: $F = \frac{Q_1Q_2}{Kd^2}$

$F = \frac{20 \times 40}{1 \times (4)^2}$

$F = \frac{800}{16}$

$F = 50$ dynes of repulsion

From Coulomb's Law, the force upon charged bodies is inversely proportional to the square of the distance between them. Therefore, as the distance between bodies is increased, the force will be decreased by the square of this distance. In this example the distance was increased by two times, therefore the force decreased by the square of two or has decreased to one-fourth its previous value.

Q12. The strength of the electrostatic force felt through glass is lower in value than the strength of the same force when passed through air. Would glass have a higher or lower dielectric constant than air?

Q13. When glass replaces air as the dielectric constant, explain by Coulomb's Law how it would be possible to retain an equal electrostatic force?

The electrostatic unit or statcoulomb which is used as a unit of charge in many experiments has been determined to represent about two billion electrons. However, even a unit representing that great a quantity of electrons is too small to use in many practical applications. In honor of Charles Coulomb another unit of electrical charge, the coulomb, is used. Experimental measurements give the value of a coulomb to be three billion electrostatic units expressed as 3×10^9 e. s. u. The coulomb is used for experimental purposes and is equivalent to 6.28 billion billion electrons and is usually written, 6.28×10^{18} electrons. This means that when a body has a positive charge of one coulomb, it has a deficiency of 6.28×10^{18} electrons. If a body has a negative charge of one coulomb it has an excess of 6.28×10^{18} electrons.

The coulomb is the unit of charge in the mks system and one with which you will frequently deal. The units of force and distance in this measurement system are the newton and the meter respectively. The coulomb as a unit of charge is not derived directly from electrostatics, therefore, when using the formula expressing Coulomb's Law with units of the mks system it is necessary to introduce a proportionality constant.

A proportionality constant, as you have learned from the study of proportion, is necessary so that the results of a mathematical problem will be dimensionally correct. This is often indicated in a formula with a small letter (k). Do not confuse this notation with capital (K) representing dielectric constant. The proportionality constant necessary to compute the force in newtons, when the charge is given in coulombs and distance in meters, is listed below:

$$k = \frac{9 \times 10^9 \text{ newton-meter}^2}{\text{coulomb}^2}$$

This constant will now be used with Coulomb's Law to compute force between bodies in the mks system. The formula for the mks system is:

$$F = k\frac{Q_1 Q_2}{Kd^2} \qquad (2\text{-}2)$$

Example 2-4. A body which has a positive charge of two coulombs is brought to a point two meters from a body possessing a positive charge of four coulombs. What is the repelling force between the charged bodies?

Given: $Q_1 = 2$ coulombs

$Q_2 = 4$ coulombs

$d = 2$ meters

$K = 1$ (dielectric constant of air)

$k = \frac{9 \times 10^9 \text{ newton-meter}^2}{\text{coulomb}^2}$

Find F:

Solution:

$$F = \frac{9 \times 10^9 \text{ n m}^2}{\text{coul}^2} \times \frac{Q_1 Q_2}{d^2}$$

$$F = \frac{9 \times 10^9 \text{ n m}^2}{\text{coul}^2} \times \frac{2 \text{ coul } 4 \text{ coul}}{(2\text{m})^2}$$

$$F = \frac{9 \times 10^9 \text{ n m}^2}{\text{coul}^2} \times \frac{8 \text{ coul}^2}{4\text{m}^2}$$

$$F = \frac{9 \times 10^9 \text{ n} \cancel{\text{m}^2}}{\cancel{\text{coul}^2}} \times \frac{\overset{2}{\cancel{8 \text{ coul}^2}}}{\underset{1}{\cancel{4\text{m}^2}}}$$

$$F = 18 \times 10^9 \text{ newtons}$$

Coulomb's Law can be applied accurately only in situations where the distance between the charges is very large compared to the dimensions of the charged bodies. Therefore, in using Coulomb's Law we consider the charge as being concentrated on a point and speak of it as being a point charge. You will find many applications for the coulomb as a unit of charge throughout your studies of electricity and electronics.

Q14. What is the difference in charge in coulombs between two bodies, one having an excess of 12.48×10^{18} electrons, the other having a deficiency of 6.24×10^{18} electrons?

DISCHARGING

2-12. Rate of Discharge

The rate at which a body is able to lose its charge is primarily determined by the size and shape of the charged body. Two metallic spheres of unequal size as shown in Figure 2-9, both having an equal charge, will each have a different rate of discharge.

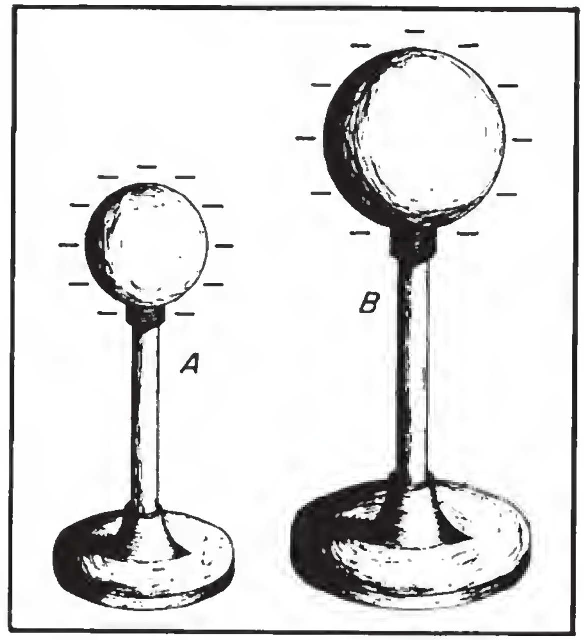

Figure 2-9 - Rate of discharge

Sphere A, though having a charge equal in magnitude to the larger sphere B, will have a greater concentration of charge per unit area. Therefore a greater pressure is developed on the smaller sphere, though the total charge of each body is equal. This greater pressure developed by the charge on sphere A will cause it to discharge at a much faster rate than the larger sphere. Discharge of bodies such as these would often occur only when making contact with a neutral body or a less negative body. However, if the charge on a spherical body is great enough, there can be a movement of electrons through an insulator such as air in an attempt to neutralize its charge.

If a charge similar to that of the metallic sphere is given to a non-uniformly curved body, there will not be the same uniform distribution of charge. An object of non-uniform curvature will accumulate most of its charge on the areas of greatest curvature. Due to the greater pressure concentrated on a very small area, the rate of discharge from these surfaces will be

A12. Higher dielectric constant.

A13. Increase magnitude of charge or decrease distance.

A14. Three coulombs.

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much faster. The more sharply pointed an object is, the faster the rate of discharge. Therefore, charges will pass off a point before many have a chance to accumulate.

Because of the electrical pressure developed by an accumulation of charge, it is necessary to have a large surface area if the build up of large quantities of charge is desired. If it is wished to have very little charge developed on an object, the object should be pointed. Although the pointed area of a body will accumulate most of the charge on the body, the pressure developed on such a small area quickly passes off these charges.

In electrostatic experiments and practical applications, a charge can easily be removed from a body by touching it with another body which has the ability to accept its charge. When the charge is great enough, contact with a charged body is not necessary for discharge to occur. The great pressure developed on an area of the charged body because of accumulated charge can cause movement of electrons in an attempt to neutralize the charge. These electrons will always move to a body which is more positive (or less negative) than their own body, thus equalizing the charges.

Q15. Explain how two spheres of equal size and shape could have different rates of discharge.

2-13. Lightning

Lightning is a common example of an electrical discharge. It is a discharge that takes place between clouds of unequal charges or between a cloud and the earth. Our present day electron theory explains the cause of lightning. With this understanding some protection from its forces has been developed.

It is believed that charges are built up on clouds due to the friction between the air and the water droplets. This friction occurs due to the uprush of the warm moist air from the earth. Droplets of water developed from the moist air are left with a charge, therefore,the clouds formed by the accumulation of these droplets take on their charge. The clouds might take on a positive or a negative charge dependent on the predominant type of charge.

The charge on a cloud, when large enough, will discharge to another cloud or to the earth. This occurrence is what we know as lightning. The thunder which accompanies lightning is caused by the sudden expansion of air due to the heat developed by this vast movement of electrons.

When lightning occurs, great damage to life and property will often be a result. The cause of this damage can be attributed to the heat produced during discharge. When discharge occurs, there is a directed movement of a vast quantity of electrons, thereby developing heat due to motion and friction. A person or object through which great quantities of electrons must pass to discharge a charged body will, therefore, be adversely affected.

With our present knowledge of electrostatics and its effects, it is now possible to minimize lightning damage. The lightning rod is a device developed for this purpose. It is not able to prevent discharges, but it is designed to discharge small quantities of charge as fast as they accumulate. This small discharge produces very little heat and is not apparent to an observer. Thus, with the proper design and connection of a lightning rod, damage due to lightning will be minimized.

Let us examine the action of a lightning rod in discharging a cloud as it passes over a home (Figure 2-10).

Due to induction, the electrostatic force about the positively charged cloud attracts many electrons toward the end of the pointed rod. The electrons accumulating on the pointed rod will easily pass off to the cloud and neutralize some of its charge. This process will be repeated until the cloud is neutralized or moves from the vicinity of the lightning rod. When the positive charges of the cloud can not be neutralized by the electrons available on the rod, electrons will be drawn up from the earth. For this reason it is very important that the lightning rod be connected by a good conductor to a rod buried several feet in the earth. Otherwise the electrons might choose to move through the house in an attempt to neutralize the positive charge of the cloud. The heat produced by the electron movement if great enough, would thereby cause a fire to occur.

Our knowledge of electrostatics also gives us some information regarding personal safety during a lightning storm. Since we know that discharge occurs most easily from pointed objects, it is not a good idea to stand in the middle of a field when lightning is present. While standing in the field, you become the easiest discharge path available to a charged cloud. The same principle holds true for a tree. The height of a tree in comparison to its surroundings make it a good discharge path. Therefore, never seek shelter underneath a

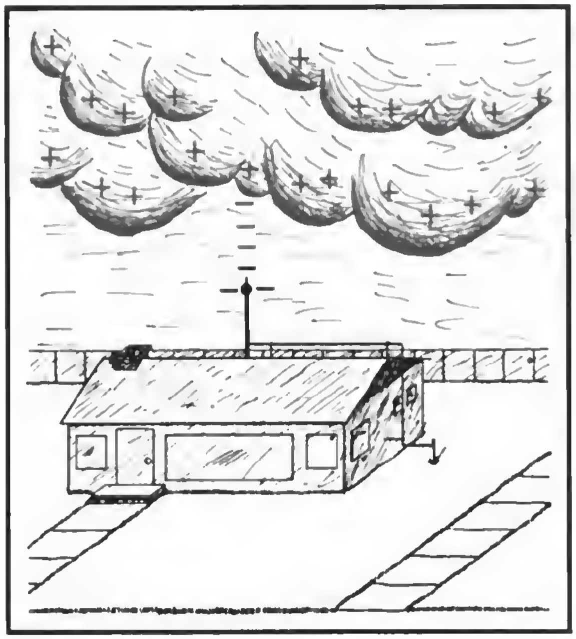

Figure 2-10 - Discharging a cloud

tree in a lightning storm.

An especially safe area for protection from lightning is inside a steel framed building which has its frame extending into the ground. Even without a lightning rod, a building of this nature becomes very safe because of the fact that all charges will appear on the outer surface of a conductor, and the steel frame provides a good conducting path to the earth.

You should now have an understanding of how a body can lose its charge by discharge. However, it should be kept in mind that whenever a certain positive charge appears on one body an equal negative charge appears on some other body or bodies. Therefore, when a body is discharged its charge will not be destroyed but is simply transferred to another body. Emphasis on the above is made by the following law:

LAW 3. Law of Conservation of Charge. The total net charge of any isolated system never changes.

Q16. Refer to Figure 2-10. Explain the effect of the lightning rod on a nearby negatively charged cloud.

Q17. Explain whether or not a car would be a comparatively safe place in a lightning storm.

ELECTRIC FIELD

2-14. Lines of Force

The area surrounding a charged body where attracting or repelling forces are felt, is known as an ELECTRIC FIELD. This field exists in a very definite pattern and is often represented by lines about the charged body. These lines, referred to as ELECTROSTATIC LINES OF FORCE, are imaginary but they help illustrate the electrical force surrounding charged bodies.

The definite pattern of this field can be seen by placing a charged body under a piece of glass and sprinkling some short brush bristles over the top of the glass. When this is done, the bristles will arrange themselves in definite directions forming somewhat of a radial pattern. This gives an indication of the intensity of the force present at various points in the field and also the ability of the electrostatic field to penetrate all substances of matter.

In illustrating the electric field surrounding a charged body, the direction of the lines of force are indicated by arrows. The magnitude of the force is indicated by the relative number of lines passing through a given region. Figure 2-11 indicates the fields of force around charged bodies.

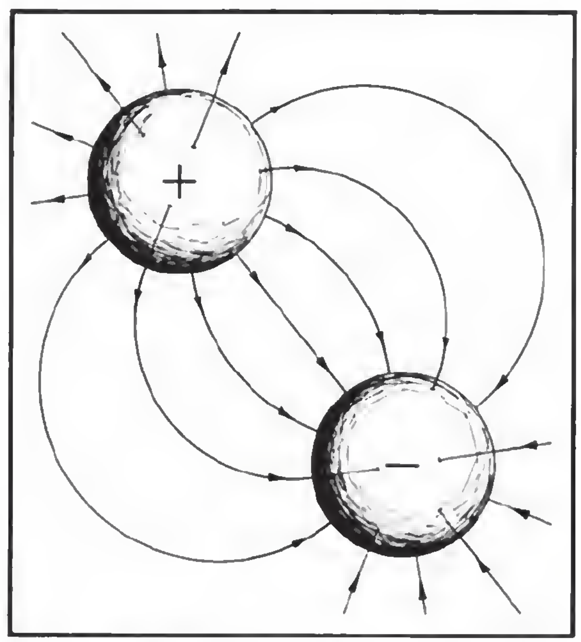

Figure 2-11 - Lines of force

2-15. Positive Test Charge

The lines of force are drawn with the field eminating from a positive charge and terminating on the negative charge. By convention, the arrowheads on the lines of force indicate

A15. Spheres possess unequal charges.

A16. The cloud is partially discharged. Electrons are passed through the rod to the earth.

A17. A safe place. All charges exist on the outside surface of a metal object.

the direction of the force that would be felt by a positive test charge inserted into the field at that point. The illustration also indicates the fact that these lines of force will never cross.

By the use of a unit positive test charge, scientists are able to measure the intensity of the force at any point in the electric field. In agreement with Coulomb's Law, the field intensity at any point near a single charged body is inversely proportional to the square of the distance from the body.

In the chapter following, another force will be examined which in many respects is very similar to the electrostatic field of force surrounding a charged body. A thorough understanding of the principle of electrostatics will be of considerable aid in the study of magnetism presented in Chapter 3.

EXERCISE 2

1. State the law of charged bodies.
2. Define the terms, (a) positive charge, (b) negative charge, (c) neutral charge.
3. List several examples of static electricity with which you are familiar.
4. Describe charging by friction.
5. What three types of energy are involved when a rubber rod is charged with cat's fur?
6. Can all materials be electrified?
7. Explain how an electrified and a non-electrified material differ.
8. Why is the type of electricity discussed in this chapter called static electricity?
9. What conditions are necessary for charging by contact to take place?
10. Describe the resultant charges on each body when a negatively charged body charges a body by contact.
11. What conditions are necessary for charging by induction to occur?
12. When a body acquires a negative charge through induction, what is the charge of the charging body?
13. Describe the resultant magnitude of charge on a charging body as it inductively charges another body.
14. List some materials which would be difficult to charge by induction.
15. What factor limits a continuous transfer of charge between charged bodies?
16. If a suspended rod is known to have been charged by a second rod, what simple experiment would determine whether the contact method or the induction method had been used to charge the suspended rod? Explain.
17. Describe the effects that would be observed if the experiment of Section 2-6 were repeated using a pith ball without a conductive coating.
18. As a rubber comb is passed through the hair, the comb will become a charged body. Describe the distribution of charges on the comb.
19. What is an electroscope?
20. State Coulomb's Law.
21. Does Coulomb's Law apply directly to all charged bodies? Explain.
22. A body has a positive charge of two coulombs. Describe the charge on the body in terms of electrons.
23. What is a dielectric constant?
24. What is a proportionality constant?
25. Two positive charged bodies are located 2 centimeters apart. One body has a charge of 2 electrostatic units and the other body has a charge of 6 electrostatic units. What is the force existing between the charges?
26. Two charged bodies exert a mutual force upon each other of 4 dynes at a distance of 4 cm. What is the force exerted as the charged bodies are brought within two cm. of each other?
27. A body with a charge of two electrostatic units is brought within 1 cm. of an equally charged body. The charged bodies are separated by a sheet of mica having a dielectric constant of three. What is the force between bodies?
28. Compare the discharging of a pointed body with the discharging of a sphere. Explain.
29. What is lightning? Explain its cause.
30. Describe the use of a lightning rod.
31. Would it be possible to create a negative charge without creating an equal amount of positive charge? Explain.
32. What is a "line of force?"
33. What is a "field of force?"
34. How do the fields of force about a positive and negative charge differ?
35. Why will two electrified bodies exert a force upon another?

CHAPTER 3

MAGNETISM

Magnetism is another invisible force which has been known to man for many centuries. However, its relationship to an electric force was not realized for some two thousand years. Early students of science believed that magnetism was a completely unrelated phenomena. In modern science the connection between the two forces is quite apparent, for without magnetism very few of our modern devices would be possible. Magnets or magnetic effects can be found in almost every modern circuit in present day use, ranging from a simple door bell to the memory units of our giant computers.

PROPERTY OF MAGNETISM

3-1. Magnetic Materials

Magnetism is generally defined as that property of a material which enables it to attract pieces of iron. A material possessing this property is known as a MAGNET. The word originated from the ancient Greeks who found stones possessing this characteristic. Materials that are attracted by a magnet such as iron, steel, nickel, and cobalt have the ability to become magnetized, these materials are called magnetic. Materials such as paper, wood, glass, or tin which are not attracted by magnets are considered non-magnetic. Non-magnetic materials are not able to become magnetized.

NATURAL AND ARTIFICIAL MAGNETS

3-2. Natural Magnets

Magnetic stones such as those found by the ancient Greeks are considered to be NATURAL MAGNETS. These stones had the ability to attract small pieces of iron in a manner similar to the magnets which are common today. However, the magnetic properties attributed to the stones were products of nature and not the result of the efforts of man. The Greeks called these substances magnetite.

The Chinese are said to have been aware of some of the effects of magnetism as early as 2600 B. C. They observed that stones similar to magnetite, when freely suspended, had a tendency to assume a nearly north and south direction. Because of the directional quality of these stones, they were later referred to as lodestones or leading stones.

Natural magnets which presently can be found in the United States, Norway and Sweden, no longer have any practical use, for it is now possible to easily produce more powerful magnets.

3-3. Artificial Magnets

Magnets produced from magnetic materials are called ARTIFICIAL MAGNETS. They can be made in a wide variety of shapes and sizes and are used extensively in electrical apparatus. Artificial magnets are generally made from special iron or steel alloys which are usually magnetized electrically. The material to be magnetized is inserted into a coil of insulated wire, and a heavy flow of electrons is passed through the wire. Magnets can also be produced by stroking a magnetic material with magnetite or with another artificial magnet. The forces causing magnetization are represented by magnetic lines of force very similar in nature to electrostatic lines of force.

Artificial magnets are usually classified as PERMANENT or TEMPORARY, depending on their ability to retain their magnetic properties after the magnetizing force has been removed. Magnets made from substances such as hardened steel and certain alloys, which retain a great deal of their magnetism, are called PERMANENT MAGNETS. These materials are relatively difficult to magnetize because of the opposition offered to the magnetic lines of force as the lines of force try to distribute themselves throughout the material. This opposition a material offers to the magnetic lines of force is called RELUCTANCE. All permanent magnets will be produced from materials having a high reluctance.

A material with a low reluctance, such as soft iron or annealed silicon steel, is relatively easy to magnetize but will retain only a small part of its magnetism once the magnetizing force is removed. Materials of this type that easily lose most of their magnetic strength are called TEMPORARY MAGNETS. The amount of magnetism which remains in a temporary magnet is referred to as its RESIDUAL MAGNETISM.

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The ability of a material to retain an amount of residual magnetism is called the RETENTIVITY of the material.

The difference between a permanent and a temporary magnet has been indicated in terms of RELUCTANCE, a permanent magnet having a high reluctance and a temporary magnet having a low reluctance. Magnets are also described in terms of the PERMEABILITY of their materials, or the ease with which magnetic lines of force distribute themselves throughout the material. A permanent magnet which is produced from a material with a high reluctance has a low permeability. A temporary magnet, produced from a material with a low reluctance would have a high permeability.

Q1. Two pieces of magnetic material are available, a section of sheet steel with a permeability of 2,310 and a section of cast steel with a permeability of 1,070. Which material would make a better permanent magnet?

Q2. Which material of the above question possesses the greater reluctance?

MAGNETIC POLES

3-4. Strength of Magnetic Poles

The magnetic force surrounding a magnet is not uniform. There exists a great concentration of force at the ends of a magnet and a very weak force at the center. Proof of this fact can be obtained by dipping a magnet into iron filings (Figure 3-1). It is found that many filings will cling to the ends of the magnet while very few adhere to the center. The two ends, which are the regions of concentrated lines of force, are called the POLES of the magnet. Magnets will usually have two magnetic poles and both poles will have equal magnetic strength.

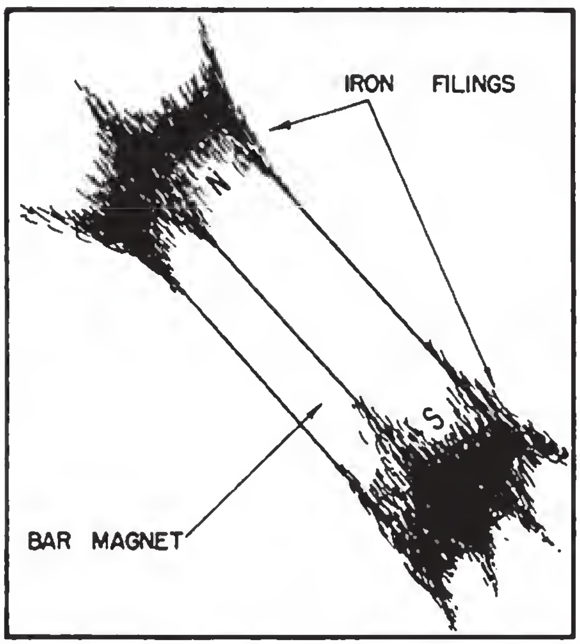

Figure 3-1 - Iron filings cling to the poles of a magnet.

3-5. Law of Magnetic Poles

If a bar magnet is suspended freely on a string, as shown in Figure 3-2, it will align itself in a north and south direction. When this experiment is repeated, it is found that the same pole of the magnet will always swing toward the north geographical pole of the earth. Therefore, it is called the north-seeking pole or simply the north pole. The other pole of the magnet is the south-seeking pole or the south pole.

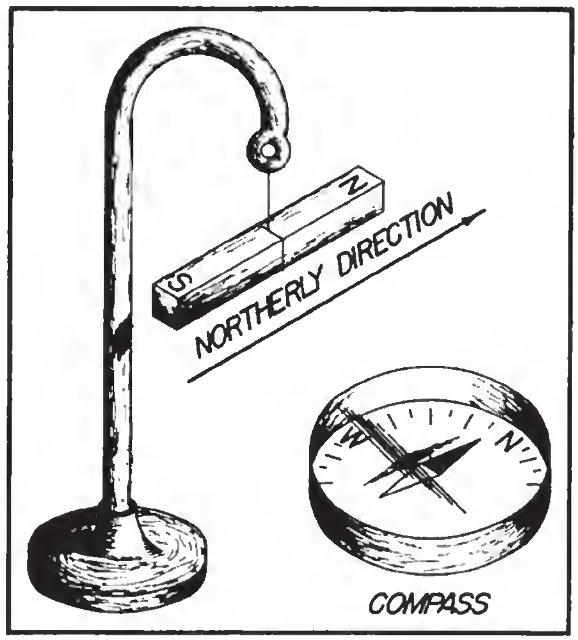

Figure 3-2 - A bar magnet acts as a compass.

A practical use of the directional characteristic of the magnet is the compass, a device in which a freely rotating magnetized needle indicator points toward the north pole. The realization that the poles of a suspended magnet always move to a definite position gives an indication that the opposite poles of a magnet have opposite magnetic polarity.

The law previously stated in Section 2-3, regarding the attraction and repulsion of charged bodies, may also be applied to magnetism if the word pole is substituted for the word charge. The north pole of a magnet will always be

attracted to the south pole of another magnet and will show a repulsion to a north pole. The law for magnetic poles is:

LAW 1. Like poles repel, unlike poles attract.

3-6. The Earth's Magnetic Poles

The fact that a compass needle always aligns itself in a particular direction, when at any location on the earth, indicates that the earth is a huge natural magnet. The distribution of the magnetic force about the earth is the same as that which might be produced by a giant bar magnet running through the center of the earth (see Figure 3-3). The magnetic axis of the earth is located about 15° from its geographical axis thereby locating the magnetic poles some distance from the geographical poles. The

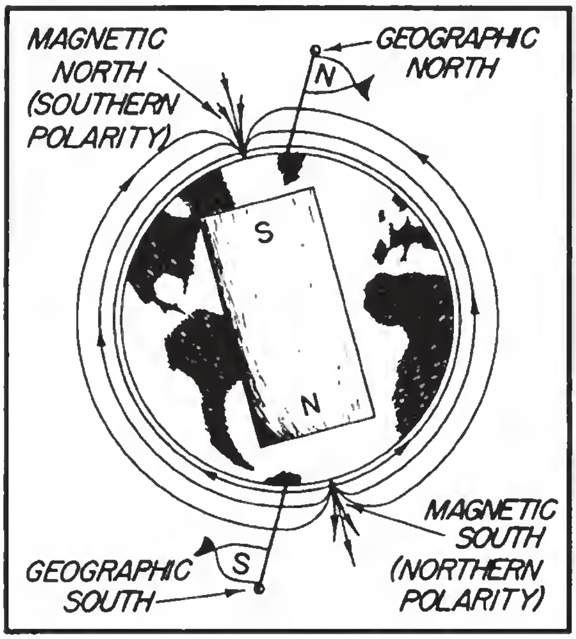

Figure 3-3 - The earth is a magnet.

ability of the north pole of the compass needle to point toward the north geographical pole is due to the presence of the magnetic pole nearby. This magnetic pole is named the magnetic north pole. However, in actuality, it must have the polarity of a south magnetic pole since it attracts the north pole of a compass needle. The reason for this conflict in terminology can be traced to the early users of the compass. Knowing little about magnetic effects, they called the end of the compass needle that pointed towards the north geographical pole, the north pole of a compass. With our present knowledge of magnetism, the north pole of a compass needle (a small bar magnet) can only be attracted by an unlike magnetic pole or a pole of south magnetic polarity.

Q3. A compass is located at the geographical north pole. In which direction would its needle point?

THEORIES OF MAGNETISM

3-7. Weber's Theory

A popular theory of magnetism considers the molecular alignment of the material. This is known as Weber's Theory. This theory assumes all magnetic substances to be composed of tiny molecular magnets. All unmagnetized materials have the magnetic forces of its molecular magnets neutralized by adjacent molecular magnets thereby eliminating any magnetic effect. A magnetized material will have most of its molecular magnets lined up so that the north pole of each molecule points in one direction, and the south pole faces the opposite direction. A material with its molecules thus aligned will then have one effective north pole, and one effective south pole. An illustration of Weber's Theory is shown in Figure 3-4 where a steel bar is magnetized by stroking. When a steel bar is stroked several times in the same direction by a magnet, the magnetic force from the north pole of the magnet causes the molecules to align themselves. The polarity of the

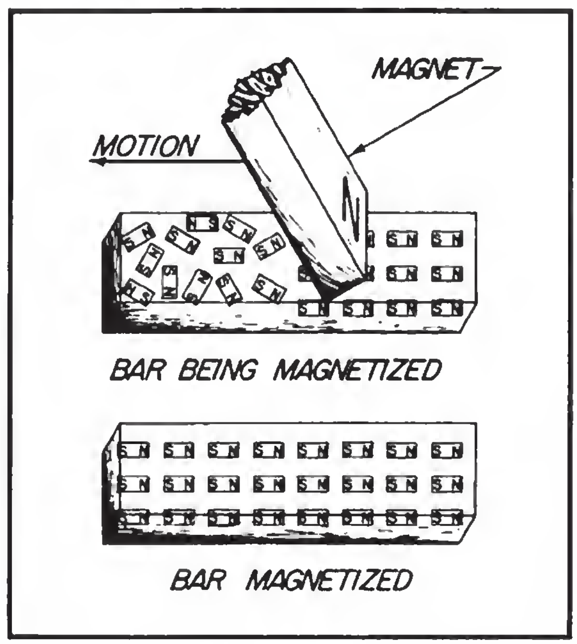

Figure 3-4 - Molecular magnets.

A1. Cast steel. A substance of lower permeability retains a greater amount of its magnetism.

A2. Cast steel.

A3. To the magnetic north pole.

magnet formed is dependent upon the direction of the magnetizing force as it is brought over the random magnetic molecules.

Some justification of Weber's Theory occurs when a magnet is split in half. It is found that each half possess both a north and a south magnetic pole as shown in Figure 3-5. The polarities of the poles are in the same respective directions as the poles of the original magnet. If a magnet is further divided into small parts, it will be found that each part, down to its last molecule, will all have similar north and south poles. Each part would exhibit its own magnetic properties.

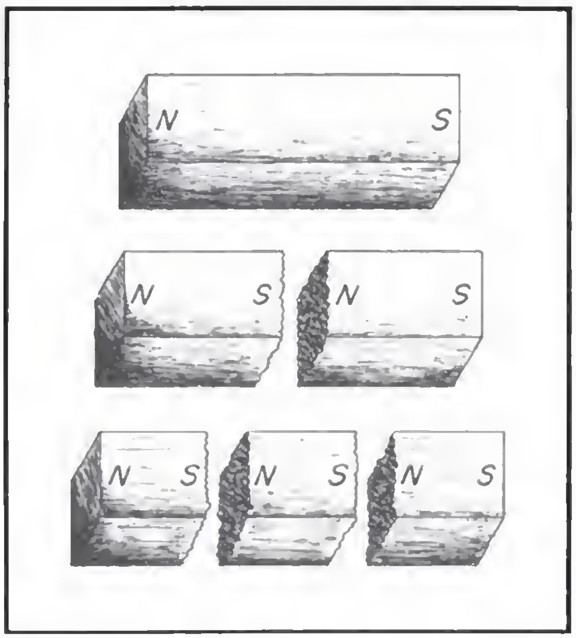

Figure 3-5 - Each piece of a magnet is a magnet.

Further support of Weber's Theory comes from the fact that when a bar magnet is held out of alignment with the earth's magnetic field and repeatedly jarred or heated, the molecular alignment is disarranged and the material becomes demagnetized. For example, measuring devices which make use of permanent magnets become inaccurate when subjected to severe jarring or exposure to opposing magnetic fields.

Q4. Using Weber's molecular theory of magnetism, describe the polarity of the magnetic poles produced by stroking a magnetic material from right to left with the south pole of a magnet.

Q5. Explain what would occur in question four if the magnetic material was stroked in an opposite direction.

3-8. Domain Theory

A more modern theory of magnetism is based on the electron spin principle. From the study of atomic structure it is known that all matter is composed of vast quantities of atoms, each atom containing one or more orbital electrons. The electrons are considered to orbit in various shells and subshells depending upon their distance from the nucleus. The structure of the atom has previously been compared to the solar system, wherein the electrons orbiting the nucleus correspond to the planets orbiting the sun. Along with their orbital motion about the sun, these planets also revolve on their axes. It is believed that the electron also revolves on its axis as it orbits the nucleus of an atom.

It has been experimentally proven that an electron has a magnetic field about it along with an electric field. The effectiveness of the magnetic field of an atom is determined by the number of electrons spinning in each direction.

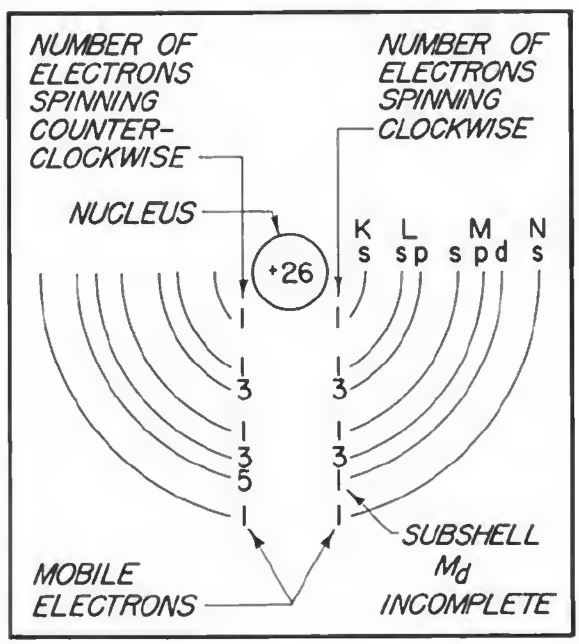

Figure 3-6 - Iron atom.

If an atom has equal numbers of electrons spinning in opposite directions, the magnetic fields surrounding the electrons cancel one another, and the atom is unmagnetized. However, if more electrons spin in one direction than another the atom is magnetized. An atom such as iron with an atomic number of 26 has twenty-six protons in the nucleus and twenty-six revolving electrons orbiting its nucleus. If thirteen electrons are spinning in a clockwise direction and thirteen electrons are spinning in a counterclockwise direction, the opposing magnetic fields will be neutralized. When more than thirteen electrons spin in either direction, the atom is magnetized. An example of a magnetized atom of iron is shown in Figure 3-6. Note that in this specific illustration the electrons magnetic fields in all except the M shell neutralize each other. As illustrated in the diagram, there exists fifteen electrons spinning in one direction and only eleven electrons spinning in an opposite direction. Therefore, the unopposed magnetic fields of four electrons will cause this iron atom to become an infinitely small magnet.

When a number of such atoms are grouped together to form an iron bar, there is an interaction between the magnetic forces of various atoms. The small magnetic force of the field surrounding an atom affects adjacent atoms, thus producing a small group of atoms with parallel magnetic fields. This group of from 10^{14} to 10^{15} magnetic atoms, having their magnetic poles orientated in the same direction, is known as a DOMAIN. Throughout a domain there is an intense magnetic field without the influence of any external magnetic field. Since about ten million tiny domains can be contained in one cubic millimeter, it is apparent that every magnetic material is made up of a large number of domains. The domains in any substance are always magnetized to saturation but are randomly orientated throughout a material. Thus, the strong magnetic field of each domain is neutralized by opposing magnetic forces of other domains. When an external field is applied to a magnetic substance the domains will line up with the external field. Since the domains themselves are naturally magnetized to saturation, the magnetic strength of a magnetized material is determined by the number of domains aligned by the magnetizing force. This more modern theory of magnetism is known as the DOMAIN THEORY.

Q6. Could domains exist in a material in which the electron spins in each atom cancel?

Q7. What happens when a permanent magnet slowly loses its magnetism over a long period of time?

LAW OF MAGNETIC FORCE

3-9. Coulomb's Law

The intensity of attraction or repulsion between magnetic poles may be described by a law almost identical to Coulomb's Law of Charged Bodies. The force between two poles is directly proportional to the product of the pole strengths and inversely proportional to the square of the distance between the poles. In the cgs system this is expressed mathematically as

$$F = \frac{m_1 m_2}{u d^2} \qquad (3\text{-}1)$$

where: F = force in dynes between two poles separated by air

m_1 = magnetic strength of first pole in unit poles

m_2 = magnetic strength of second pole in unit poles

d = distance between poles in cm.

u = permeability of the medium through which the force acts

The magnetic strength of each magnetic pole is measured in UNIT POLES. A unit pole has a strength such that when placed one centimeter from an equal pole (in air or vacuum), there

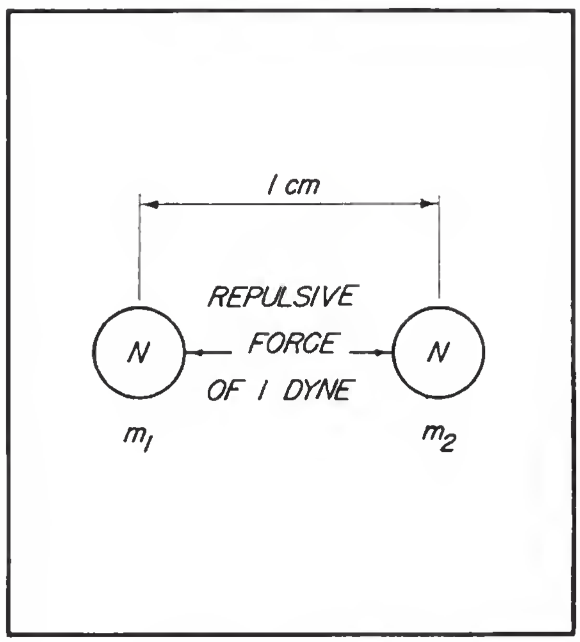

Figure 3-7 - A unit pole.

A4. South pole at the right, north pole at the left.

A5. Magnetic poles would have been reversed.

A6. No. The spins must be unbalanced before domains can form.

A7. The domains gradually become disarranged.

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will be a force exerted of one dyne (See Figure 3-7). This can be a force of either attraction or repulsion depending on the polarity of the poles.

Example. A south pole with a strength of forty unit poles is placed ten centimeters from a north pole having a magnetic strength of twenty unit poles. What is the magnitude of the force between the two poles?

Given: $m_1 = -40$ unit poles

$m_2 = 20$ unit poles

$d = 10$ centimeters

$u = 1$

Find F:

Solution:

$$F = \frac{(-m_1)(m_2)}{ud^2}$$

$$F = \frac{-40 \times 20}{1 \times 10^2}$$

$$F = \frac{-800}{100}$$

$$F = -8$$

F = 8 dynes of attraction

NOTE 1. Unit pole strengths are expressed as positive quantities for north poles and negative quantities for south poles. Resultant forces of a positive value indicate a force of repulsion; a negative value force indicates attraction.

NOTE 2. The permeability (u) indicates the ease with which magnetic lines of force can pass through a medium. It is similar to the dielectric constant used with electrical forces. Air is the standard reference and is given a numerical value of one. Any problems in which permeability is not mentioned considers air to be the medium through which the force is felt.

Q8. If the distance separating two north poles is doubled, and at the same time the strength of each pole is doubled, what will be the resultant effect on the force between the poles?

MAGNETIC FIELDS

3-10. Field Pattern

The space surrounding a magnet where magnetic forces act is known as the magnetic field. One method used to obtain knowledge pertaining to a magnetic field is to explore the field with a compass. This is similar to the test charge method used to explore an electrostatic field in Section 2-10. By use of a compass, the characteristics of the magnetic field

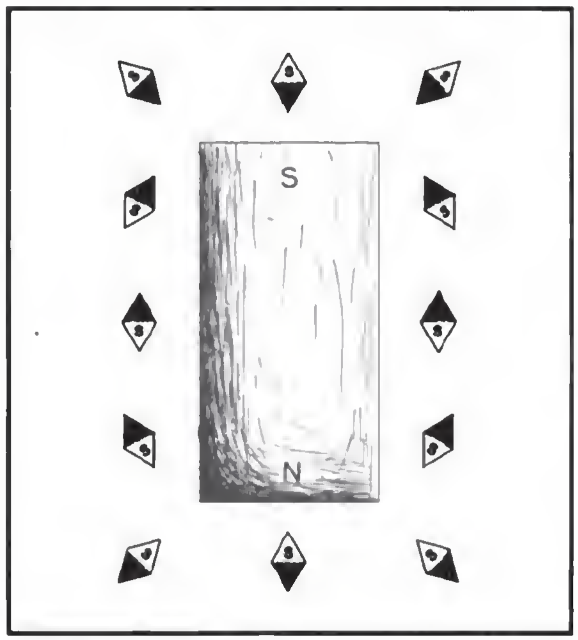

Figure 3-8 - Exploring a magnetic field with a compass.

at various points near a magnet may be observed. Figure 3-8 shows the behavior of a compass needle as the compass is used to explore the field about a simple bar magnet. Notice that the compass needle aligns itself in various positions as it is placed at different points in the magnetic field. The alignment of the compass needle indicates a definite line of direction to the magnetic field.

A pattern of this directional force can be obtained by performing an experiment with iron filings. A piece of glass is placed over a bar magnet and the iron filings are then sprinkled

on the surface of the glass. The magnetizing force of the magnet will be felt through the glass and each iron filing becomes a temporary magnet. If the glass is now tapped gently, the iron particles will align themselves with the magnetic field surrounding the magnet just as the compass needle did previously. The filings form a definite pattern, which is a visible representation of the forces comprising the magnetic field. Examination of the arrangement of the iron filings in Figure 3-9 will indicate that the magnetic field is very strong at the poles and weakens as the distance from the poles increases. It is also apparent that the magnetic field extends from one pole to the other constituting a loop about the magnet.

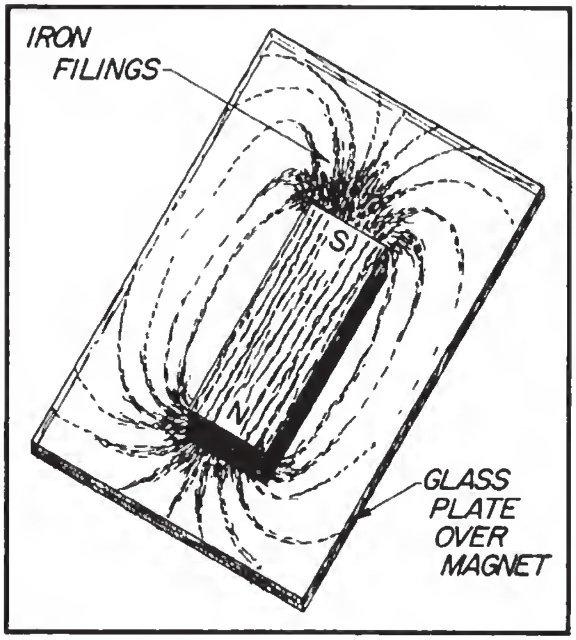

Figure 3-9 - Pattern formed by iron filings.

Q9. What pattern would be formed if sawdust was sprinkled on the glass instead of iron filings?

3-11. Lines of Force

To further describe and work with magnetic phenomena, lines are used to represent the force existing in the area surrounding a magnet (refer to Figure 3-10). These lines, called MAGNETIC LINES OF FORCE, do not actually exist but are imaginary lines used to illustrate and describe the pattern of the magnetic field. The magnetic lines of force are assumed to eminate from the north pole of a magnet, pass through the surrounding space, and enter the south pole. The lines of force then travel inside the magnet from the south pole to the north pole thus completing a closed loop.

When two magnetic poles are brought close together, the mutual attraction or repulsion of the poles produces a more complicated pattern than that of a single magnet. These magnetic

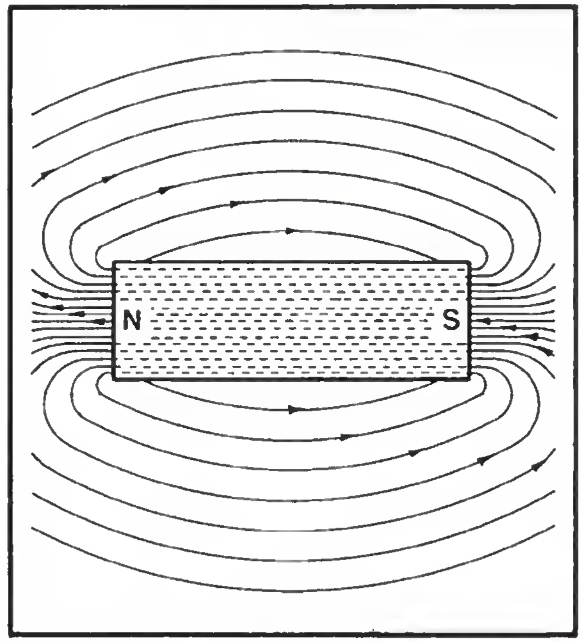

Figure 3-10 - Bar magnet showing lines of force.

lines of force can be plotted by placing a compass at various points throughout the magnetic field, or they can be roughly illustrated by the use of iron filings as before. A diagram of magnetic poles placed close together is shown in Figure 3-11.

Although magnetic lines of force are imaginary, a simplified version of many magnetic phenomena can be explained by assuming the magnetic lines to have certain real properties. The lines of force can be compared to rubber bands which stretch outward when a force is exerted upon them and contract when the force is removed. The characteristics of magnetic lines of force can be described as follows:

1. Magnetic lines of force are continuous and will always form closed loops.

2. Magnetic lines of force will never cross one another.

3. Parallel magnetic lines of force travelling in the same direction repel one another. Parallel magnetic lines of force travelling in opposite directions tend to unite with each other and form into single lines travelling in a direction determined by the magnetic

A8. The force would remain the same.

A9. No specific pattern, sawdust is a non-magnetic material.

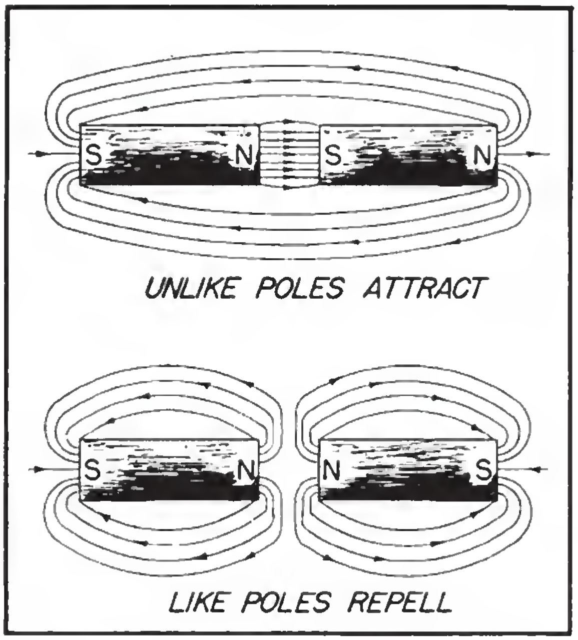

Figure 3-11 - Magnetic poles in close proximity.

poles creating the lines of force.

4. Magnetic lines of force tend to shorten themselves. Therefore, the magnetic lines of force existing between two unlike poles cause the poles to be pulled together.

5. Magnetic lines of force pass through all materials, both magnetic and non-magnetic.

6. Magnetic lines of force always enter or leave a magnetic material at right angles to the surface.

Q10. In what way do magnetic lines of force differ from electrostatic lines of force?

3-12. Magnetic Flux

The total number of magnetic lines of force leaving or entering the pole of a magnet is called MAGNETIC FLUX. The number of flux lines per unit area is known as FLUX DENSITY. This relationship can be expressed as an equation:

$$B = \frac{\phi}{A} \qquad (3\text{-}2)$$

where the Greek letter beta (B) represents flux density, the Greek letter phi (ϕ) represents total magnetic lines of flux, and A is the cross-sectional area. Most units of measure in magnetic studies are named in honor of scientists who worked with magnetics. The unit of flux density (B) is the GAUSS, and the unit of magnetic flux is the MAXWELL equal to one line of magnetic flux. Area is measured in square centimeters.

The above mathematical equation shows the proportional relationship between the different units and can be accurately used only with a uniform magnetic field. That is, a field where each square centimeter contains exactly the same number of lines. The flux density of the magnetic field at a pole of a magnet can be accurately calculated with the given equation.

Example. A magnetic pole has a flux of 300, 000 maxwells. The cross-sectional area of the magnetic pole is 50 square centimeters. What is the flux density of the magnetic field at the pole?

Given: ϕ = 300, 000 maxwells

A = 50 square centimeters

Find B:

Solution:

$$B = \frac{\phi}{A}$$

$$B = \frac{300,000}{50}$$

$$B = 6000 \text{ gauss}$$

Q11. A bar magnet has a flux density at its pole of 1200 gauss. Describe the magnitude of flux density as it would exist a short distance from the magnetic pole.

3-13. Field Intensity

The intensity of a magnetic field is directly related to the magnetic force exerted by the field. The unit used in measuring field intensity is the OERSTED, one oersted being equal to the strength necessary to exert a force of one dyne per unit pole. This relationship may be expressed mathematically as:

$$H = \frac{f}{m} \qquad (3\text{-}3)$$

where: H = field intensity in oersteds

f = force acting upon a magnetic pole in dynes

m = strength of magnetic pole in unit poles

Example. What is the intensity of a magnetic field that exerts a force of 100 dynes on a magnet having a strength of 50 unit poles?

Given: f = 100 dynes

m = 50 unit poles

Find H:

Solution:

$$H = \frac{f}{m}$$

$$H = \frac{100}{50}$$

$$H = 2 \text{ oersteds}$$

Q12. Refer to example. If a magnet with double the pole strength is brought into the magnetic field and the same force is exerted on the pole, what change in field intensity must have occurred?

3-14. Magnetic Induction

It has previously been stated that all substances that are attracted by a magnet are capable of becoming magnetized. The fact that a material is attracted by a magnet indicates the material must itself be a magnet at the time of attraction. Coulomb's Law gives proof of this statement, for if a material was not magnetized there could be no magnetic force exerted upon it. Referring to the mathematical expression of Coulomb's Law below, it is easily seen that the magnetic force between a magnetized body and a non-magnetized body is always equal to zero. (In special cases to be explained later, a force may exist if there is relative motion between two bodies.)

Proof:

$$F = \frac{m_1 m_2}{ud^2} \qquad (3\text{-}1)$$

$$F = \frac{0 \times m_2}{ud^2}$$

$$F = \frac{0}{ud^2}$$

$$F = 0 \text{ dynes}$$

With the knowledge of magnetic fields and magnetic lines of force developed up to this point, it is simple to understand the manner in which a material becomes magnetized when brought near a magnet. As an iron nail is brought close to a bar magnet, Figure 3-12, some flux lines emanating from the north pole of the magnet pass through the iron nail in completing their magnetic path. Since magnetic lines of force travel inside a magnet from the south pole to the north pole, the nail will be magnetized in such a polarity that its south pole will be adjacent to the north pole of the bar magnet. There is now an attraction between the two magnets.

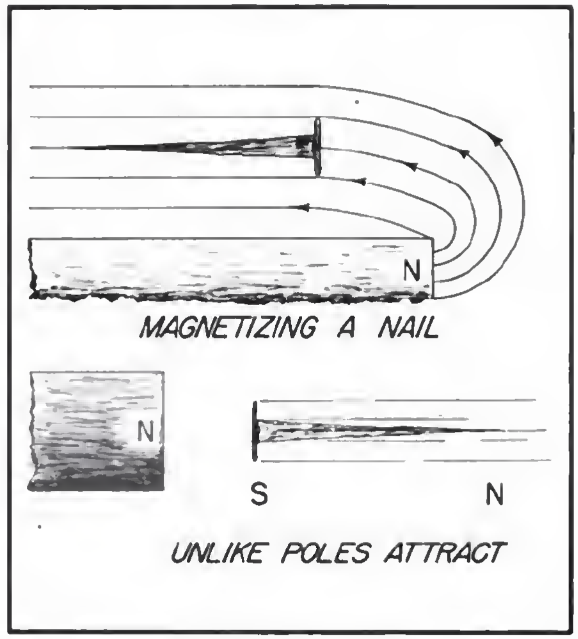

Figure 3-12 - Magnetized nail.

If another nail is brought in contact with the end of the first nail, it would be magnetized by induction. This process could be repeated until the strength of the magnetic flux weakens as distance from the bar magnet increases. However, as soon as the first iron nail is pulled away from the bar magnet, all the nails will fall. The reason being that each nail becomes a temporary magnet, and as soon as the magnetizing force is removed, their domains once again assume a random distribution.

Magnetic induction will always produce a pole polarity on the material being magnetized opposite that of the adjacent pole of the magnetizing force. It is sometimes possible to bring a weak north pole of a magnet near a strong magnet north pole and note attraction between the poles. The weak magnet, when placed

A10. Electrostatic lines of force do not form closed loops.

A11. Flux density would decrease.

A12. The field intensity must have decreased to half its previous value.

within the magnetic field of the strong magnet, has its magnetic polarity reversed by the field of the stronger magnet. Therefore, it is attracted to the opposite pole. For this reason, it is wise to keep a very weak magnet, such as a compass needle, away from a very strong magnet.

Magnetism can be induced in a magnetic material by several means. The magnetic material may be placed in the magnetic field, brought into contact with a magnet, or stroked by a magnet. Stroking and contact both indicate actual contact with the material but are considered in magnetic studies as magnetizing by induction.

Q13. What determines the polarity of a temporary magnet produced by induction?

Q14. Explain how the south pole of the magnet in Figure 3-12 would attract an iron nail.

MAGNETIC MATERIALS

Early magnetic studies classified materials merely as being magnetic and non-magnetic. Present studies classify materials into one of three groups, namely, paramagnetic, diamagnetic, and ferromagnetic.

3-15. Paramagnetic and Diamagnetic Materials

PARAMAGNETIC materials are those that become only slightly magnetized even though under the influence of a strong magnetic field. This slight magnetization is in the same direction as the magnetizing field. Materials of this type are aluminum, chromium, platinum, and air.

DIAMAGNETIC materials can also be only slightly magnetized when under the influence of a very strong field. These materials, when slightly magnetized, are magnetized in a direction opposite to the external field. Some diamagnetic materials are copper, silver, gold, and mercury.

Paramagnetic and diamagnetic materials have a very low permeability. Paramagnetic materials have a permeability slightly greater than one; diamagnetic materials have a permeability less than one. Because of the difficulty in obtaining some magnetization of paramagnetic and diamagnetic materials, these materials are considered for all practical purposes as non-magnetic materials.

3-16. Ferromagnetic Materials

The most important group of materials for applications of electricity and electronics are the ferromagnetic materials. Ferromagnetic materials are those which are relatively easy to magnetize such as iron, steel, cobalt, Alnico, and Permalloy, the latter two being alloys. Alnico consists primarily of aluminum, nickel and cobalt. These new alloys can be very strongly magnetized with Alnico capable of obtaining a magnetic strength great enough to lift five hundred times its own weight.

Ferromagnetic materials all have a high permeability. However, as previously discussed, a material such as steel used to make a permanent magnet, is considered to have a relatively low permeability in comparison to other ferromagnetic materials.

MAGNETIC SHIELDING

3-17. Magnetic Paths

There is not a known insulator against magnetic flux. Any material, when placed within a magnetic field, will be penetrated by the passage of magnetic flux. For example, the glass when placed over the bar magnet in the iron filing experiment did not stop the penetration of the magnetic field. Nor would have paper, copper, gold, or any other non-magnetic material.

Since it is not possible to block magnetic fields by offering a high opposition to them, often needed protection from magnetic forces is obtained by redirecting the field. If a magnetic material such as soft iron is placed within a magnetic field, most of the lines of force, which take the easiest path, will pass through the magnetic material while completing a closed loop (see Figure 3-13).

Q15. Why don't all the lines of force take the path through the soft iron in Figure 3-13?

Application of the above information is necessary to protect the sensitive mechanism of electric instruments as such instruments become inaccurate when subjected to the influence of stray magnetic fields. Because an instrument's mechanism cannot be insulated from magnetic flux, it is necessary to redirect the passage of the flux lines. It is known that the magnetic

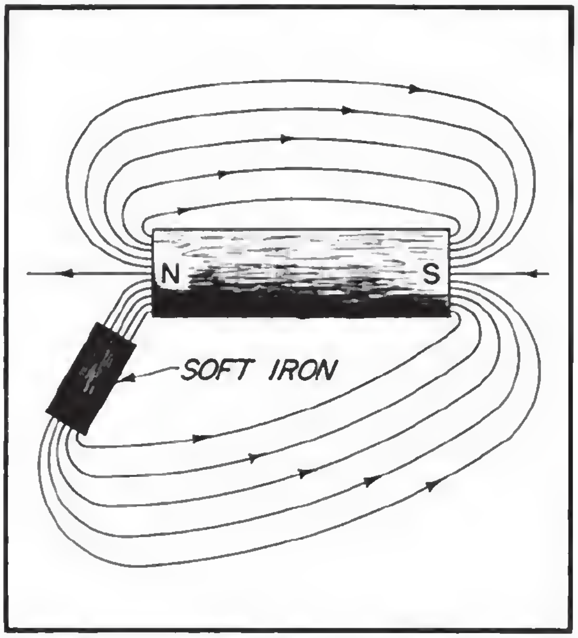

Figure 3-13 - Lines of force concentrated on soft iron.

lines of force take the path of least opposition, therefore, if we surround an object with a material having a high permeability the magnetic lines taking the easiest path will flow through the surrounding material. A senstivie instrument is protected by enclosing it in a soft iron case called a MAGNETIC SCREEN or SHIELD as shown in Figure 3-14. It must be emphasized again that there is no insulator for magnetic lines of force, but by placing an instrument inside the iron shield, an insulating effect occurs.

MAGNETIC SHAPES

Because of the many uses of magnets, they are found in various shapes and sizes. However, magnets usually come under three general classifications, namely, bar magnets, horseshoe magnets, and ring magnets.

3-18. Bar and Ring Magnets

The bar magnet is most often used in schools and laboratories for studying the properties and effects of magnetism. In the preceding text material the bar magnet proved very helpful in demonstrating magnetic effects.

Another type of magnet is the ring magnet used for computer memory cores. A common application for a temporary ring magnet would be the shielding of electrical instruments as previously discussed.

3-19. Horseshoe Magnet

The shape of the magnet most frequently used in electrical or electronic equipment is called the horseshoe magnet. A horseshoe magnet is similar to a bar magnet but is bent in the shape of a horseshoe. The horseshoe magnet

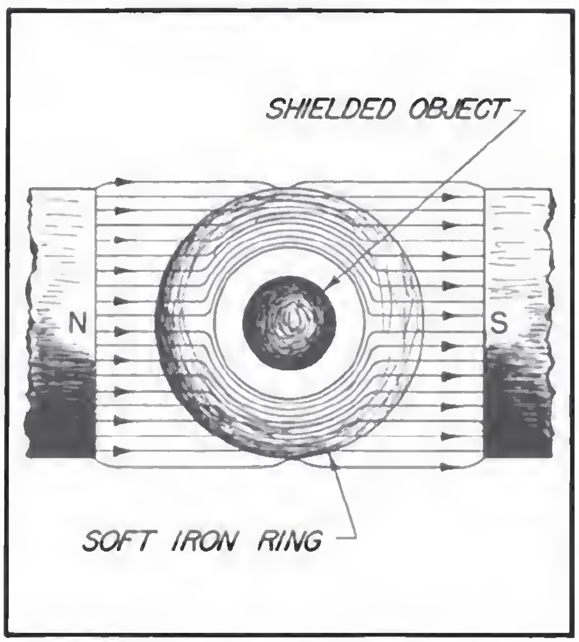

Figure 3-14 - Magnetic shielding.

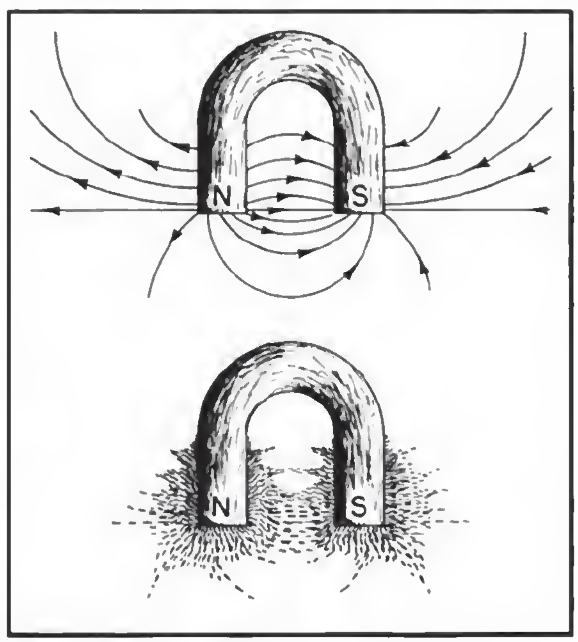

Figure 3-15 - Horseshoe magnet.

A13. The direction of the magnetizing flux lines as they pass through the material.

A14. The nail is magnetized in such a direction that its north pole is adjacent to the south pole of the bar magnet. Opposite poles attract.

A15. Each line of force takes the path of least opposition.

---

provides much more magnetic strength than a bar magnet of the same size and material because of the closeness of the magnetic poles. The magnetic strength from one pole to the other, as illustrated in Figure 3-15, is greatly increased due to the concentration of the magnetic field in a smaller area. Electrical measuring devices quite frequently use horseshoe type magnets.

CARE OF MAGNETS

3-20. Effects of Heat and Vibration

A piece of steel that has been magnetized can lose much of its magnetism by improper handling. If it is jarred or heated, there will be a disalignment of its domains resulting in the loss of some of its effective magnetism. Had this steel formed the horseshoe magnet of a meter, the meter would no longer be operable or would give inaccurate readings. Therefore, care must be taken when handling instruments containing permanent magnets. Severe jarring or subjecting the instrument to high temperature will damage the device.

3-21. Flux Leakage

A magnet may also become weakened from loss of flux. Thus, when storing these magnets one should always try to avoid excess leakage of magnetic flux. A horseshoe magnet should always be stored with a keeper, a soft iron bar used to join its magnetic poles. By use of the keeper while the magnet is being stored, the magnetic flux will continuously circulate through the magnet and not leak off into space.

When storing bar magnets, the same principle must be kept in mind. Therefore, bar magnets should always be stored in pairs with a north pole and a south pole placed together. This provides a complete path for the magnetic flux without any flux leakage.

In this chapter the basic laws and principles of magnetism have been studied. The knowledge obtained provides a background for later studies where magnetism will be frequently related to electricity.

EXERCISE 3

1. Describe the basic difference between magnetic and non-magnetic materials.
2. What are the advantages of artificial magnets in comparison to natural magnets?
3. What term is used to describe the magnetism remaining in a soft iron bar once the magnetizing force is removed?
4. Define the terms (a) reluctance, (b) permeability.
5. Can a material with a high permeability be easily magnetized? Explain.
6. Does a material with a high reluctance easily lose its magnetism? Explain.
7. Describe the strength of the magnetic force at various points surrounding a bar magnet.
8. Compare the law of magnetic poles with the law of charged bodies.
9. Explain why the north magnetic pole of a compass needle points toward the earth's north geographical pole.
10. Using Weber's Theory of magnetism, describe the effect on a magnet when it is improperly handled.
11. What two forces surround every electron?
12. Can a magnet have one magnetic pole?
13. Do all materials contain magnetism? Explain.
14. Give a description of a domain.
15. State Coulomb's Law of magnetic force.
16. A magnetic north pole of 500 unit pole strength and a south pole of 200 unit pole strength are placed 10 cm. apart in air, what is the force acting on the poles?
17. Compare the terms permeability and dielectric constant.
18. What is a magnetic field?
19. What is a magnetic line of force?
20. Compare magnetic lines of force to electrostatic lines of force.
21. Define the term flux density.
22. Compare magnetic induction to electrostatic induction.
23. Can a substance that is not a magnet be attracted by a magnet? Explain.
24. What methods are available for magnetizing by induction?
25. Would a good electrical insulator make a good magnetic insulator? Explain.
26. Compare the strength of a horseshoe magnet with that of a bar magnet.
27. When storing bar magnets, why are the magnets kept in pairs?
28. What is the flux density of a magnet that has 300 maxwells of magnetic flux and a cross-sectional area of 60 square centimeters?

CHAPTER 4

VOLTAGE

In every system in which a transformation of energy occurs, there must be a primary agent which supplies the initial energy to the system. In the system of wires and components that make up an electric circuit this primary agency is commonly referred to as the SOURCE for the circuit. Flashlight cells and automobile batteries are good examples of electrical sources.

Although a device which supplies electrical energy to a circuit is called the source, it must be remembered that the source does not create energy. The source is merely a device in which some other form of energy is transformed into electrical energy. In the case of a battery, chemical energy is converted into electrical energy.

As an aid to the study of electrical sources, a foundation will first be laid by an investigation of forces exerted by the earth's gravitational field.

EFFECTS OF GRAVITY

4-1. Gravitational Field

Most people are aware that a gravitational field surrounds the earth. This field is evidenced by the fact that all objects in our environment are attracted to the center of the earth with a force that is proportional to the mass of the object. A person is made very much conscious of this force by the physical labor required to lift a heavy object from its resting place on the surface of the earth. At times, this force of gravity can cause undesirable effects, such as when a delicate piece of glassware slips from ones hands and is pulled with shattering results to the floor.

Fortunately, the force of gravity does not always work to our disadvantage. It is this very force which enables man to cling to the earth's surface and which prevents the life giving gasses of the atmosphere from escaping into space.

Q1. Why does a liquid such as water always seek the lowest possible level?

WORK AND ENERGY

4-2. The Meaning of Work

In everyday life, WORK is commonly thought of as anything that requires physical or mental exertion. In the field of physical science, however, work must be defined more precisely. WORK IS THE PRODUCT OF DISPLACEMENT AND FORCE. The amount of work accomplished by movement of an object can be calculated by the equation:

$$W = Fd \qquad (4\text{-}1)$$

Where: W = work performed

F = force applied in direction of displacement

d = distance through which the force acts

Since the metric units for force and displacement (distance) are the newton and the meter respectively, work is measured in newton-meters. One newton-meter has been named the JOULE in honor of James Prescott Joule, a British physicist who developed important theories concerning work. One joule of work is done when a force of one newton acts through a distance of one meter.

The amount of work represented by one joule can be illustrated by the following example. If a mass weighing three-quarters of a pound (at sea level) is raised a distance of one foot, the work accomplished is approximately one joule.

It is important to notice that according to the precise definition of work, no work is accomplished unless the force applied causes a change in position of a stationary object, or a change in velocity of a moving object. A man may tire himself by pushing against a heavy wooden box, but unless the box moves as a result of his efforts, he has accomplished no work.

Q2. Is any work accomplished when a billiard ball, rolling across a table, collides with a second ball? Explain.

A1. The force of gravity causes all mass to be attracted toward the center of the earth.

A2. Yes. The energy contained in the object in motion is imparted to the stationary object. The second ball will commence rolling.

4-3. Kinetic Energy

Whenever work is accomplished on an object ENERGY is consumed (changed from one kind to another). If no energy is available, no work can be performed. Thus: ENERGY IS THE ABILITY TO DO WORK.

One form of energy is that which is contained by an object in motion. In driving a nail into a block of wood a hammer is set in motion in the direction of the nail. As the hammer strikes the nail, the energy of motion of the hammer is converted into work as the nail is driven into the wood. Energy contained by an object due to its motion is called KINETIC ENERGY.

4-4. Potential Energy

In addition to kinetic energy, an object can contain energy by virtue of its position within a system. A hammer and the earth form a system of masses in which exchanges of energy can take place through the medium of the earth's gravitational field. Assume that the hammer is suspended by a string in a position one meter above a nail. As a result of gravitational attraction, the hammer will experience a force pulling it downward toward the center of the earth. If the string is suddenly cut, the force of gravity will pull the hammer downward against the nail, driving it into the wood. While the hammer is suspended above the nail it has ability to do work because of its elevated position in the earth's gravitational field. Since energy is the ability to do work, the hammer contains energy.

Energy contained by an object due to its position is called POTENTIAL ENERGY. The amount of potential energy available is equal to the product of the force required to elevate the object and the height to which it is elevated.

Q3. Describe the energy contained by a child's swing (a) as it is poised at the top of its back-swing, and (b) as it reaches the lowest point of its arc.

4-5. Potential Difference

In most cases the total potential energy in a system is of little practical importance. A good example of this is the old fashioned cuckoo clock. Figure 4-1A shows such a clock in which the gear mechanism used to turn the hands is operated by a slowly falling weight. In Figure 4-1B, a metal weight is suspended on a chain beneath the clock, so that the gear will be rotated as the weight pulls downward on the chain. With a given length of chain, the weight can only fall a short distance to position X, its lowest possible position. To begin, assume that the weight having a mass of one kilogram, is at position X. If the weight is then raised against the force of gravity from position X to position Y, a distance

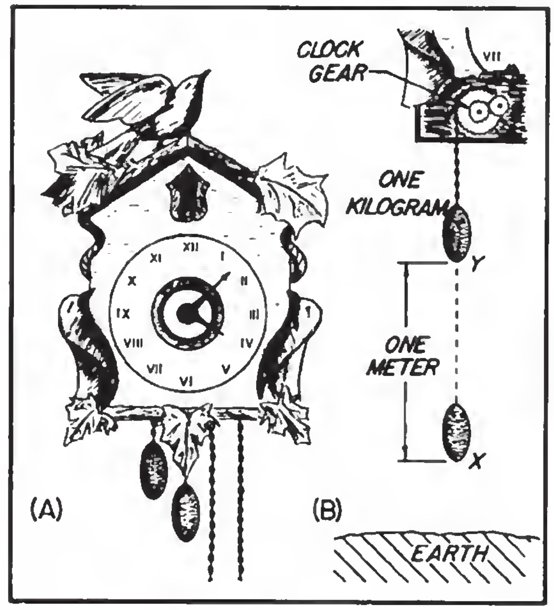

Figure 4-1 - Weight driven cuckoo clock.

of one meter, work will have been performed on the weight. The force required to overcome gravity is known to be 9.8 newtons for a mass of one kilogram. The work accomplished can be calculated by the use of equation (4-1) as follows:

Given: $F = 9.8$ newtons

$d = 1.0$ meter

Solution:

$$W = Fd \qquad (4\text{-}1)$$

$$W = 9.8 \text{ newtons} \times 1.0 \text{ meter}$$

$$W = 9.8 \text{ joules}$$

Thus, the work accomplished in raising the weight from position X to position Y is found to be 9.8 joules.

A close examination of the above example shows that the weight now has capabilities which it did not have when it was in position X. If the weight is allowed to fall from Y to X, work will be accomplished by the weight as it falls. Neglecting friction, the amount of work recovered when the weight falls is 9.8 joules, exactly equal to the work expended in raising the weight.

It is no mere coincidence that the work required to raise the weight (9.8 joules) and the amount of work the raised weight is able to perform are equal. This equality stems from one of the fundamental laws of physics which states that energy can be neither created nor destroyed but can be transformed from one kind to another.

The potential energy gained by a body is equal to the work done on that body in moving it from its original position to its final position. Since 9.8 joules of work was done on the clock weight in raising it from position X to position Y, the weight gained 9.8 joules of potential energy.

In the case of the clock-weight it must be stressed that the weight in position Y did not contain a total of 9.8 joules of energy. It GAINED 9.8 joules of energy in addition to the energy it contained in position X. For the weight to have zero potential energy it would have to be placed at the earth's center of gravity. Since the weight could not possibly fall all the way to the earth's center, the total potential energy of the weight could never be fully utilized. Of far greater interest is the additional energy that is added to the system as the weight is raised from its lowest position to its highest position, since this represents the amount of energy which can be recovered as work.

To simplify problems dealing with potential energy, the lowest position of a body is used as a reference point and the body is considered to have zero potential energy when in this position. (This simplification is similar to the system used in measuring altitude where sea level, rather than the center of the earth, is used as the zero reference). The potential energy of the upper position of the body could then be computed with respect to the lower position. The result would be the DIFFERENCE OF POTENTIAL between the two positions and a true measure of the work that may be recovered. In future calculations the difference of potential energy will be considered rather than the absolute potential energies.

Q4. What is the numerical relationship between work and potential energy?

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WORK AND ELECTRICAL ENERGY

4-6. The Electric Field

From the previous study of electrostatics it was learned that a field of force exists in the space surrounding a quantity of charge. This field of force, although electrical in nature, is very similar to the earth's gravitational field. As a result of this similarity, many of the laws developed for the gravitational field apply equally as well to the electric field.

For the purpose of explanation assume that a positive charge of magnitude Q_1 exists at an isolated point in space as shown in Figure 4-2. As illustrated in the drawing, the space around charge Q_1 is filled with an electric field of force. The field of force is theorized to consist of electrostatic lines of force, each line of which starts at the surface of the charge and extends outward to infinity. This field is seen to be very dense in close proximity to charge Q_1, but diminishes rapidly in intensity as the distance from Q_1 is increased.

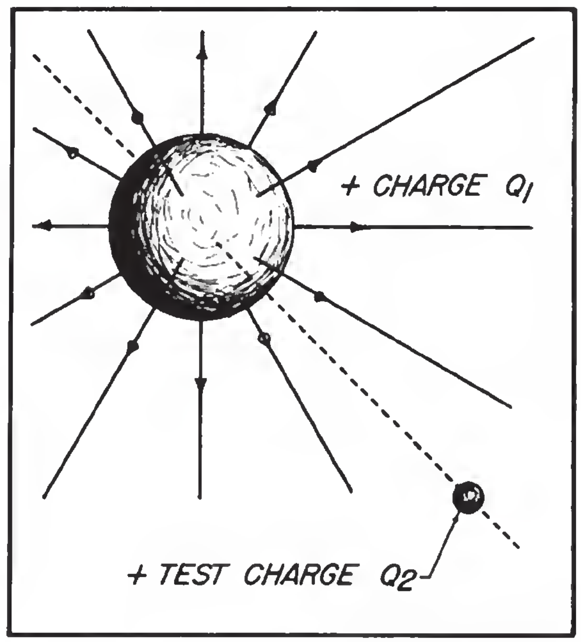


Figure 4-2 - Electric field surrounding a positive charge.

4-7. Electrical Potential Energy

If a positive test charge of magnitude Q_2 is inserted into the electrical field of charge Q_1 (described above) a situation exists similar to that of the weight placed into the gravitational field of the earth. If charge Q_2 is initially placed into the field at an infinite distance from charge Q_1, little or no force would be exerted on Q_2 by charge Q_1. For practical purposes the

A3. (a) All the energy is potential.
(b) All the energy is kinetic.

A4. The potential energy is equal to the work done on the body. Numerically they are the same.

---

intensity of the field about charge Q_1 could be considered to be zero at this remote distance. Since the test charge is resting at a point of zero force, it contains no potential energy and therefore does not have the ability to do work. This would be analogous to an object being placed at the earth's center of gravity where complete equilibrium would exist.

If now by some method, the test charge is caused to move from infinity to a point of relative proximity to charge Q_1, energy will be expended in overcoming the repelling effect caused by the interaction between the electric fields of the two like charges. This expended energy is converted into ELECTRICAL POTENTIAL ENERGY and stored in the test charge. Each time the test charge is moved to a position closer to charge Q_1, work is performed and the test charge gains additional potential energy. From equation 4-1, the work accomplished is:

$$W = Fd \qquad (4\text{-}1)$$

Since the force required to move the test charge against the electric field is:

$$F = k\frac{(Q_1Q_2)}{d^2} \qquad (2\text{-}2)$$

by substitution of equation 2-2 into equation 4-1 we obtain:

$$W = k\frac{(Q_1Q_2)d}{d^2}$$

therefore:

$$W = k\frac{(Q_1Q_2)}{d} \qquad (4\text{-}2)$$

Q5. Would any work be performed if, in the above example, the test charge were negative? Explain.

4-8. Electrical Potential Difference

Refer again to the previous example charges. If the test charge Q_2 is held in a stationary position in the electric force field of charge Q_1, a condition exists which is comparable to the situation of the raised clock-weight in paragraph 4-5. The raised weight contained potential energy due to its elevated position in the earth's gravitational field. As the weight was allowed to slowly fall, its potential energy was converted into useful work as it turned the gears and hands of the clock. A similar comparison can be made to the stationary test charge since it also contains potential energy. If the test charge is allowed freedom of movement it will be repelled from the point charge Q_1, along the dotted line as shown in Figure 4-2. Since work was defined as force times distance, the test charge accomplishes work as it is repelled from charge Q_1. All of the energy that was expended in moving Q_2 toward Q_1 was stored in Q_2 and will now be recovered (in the form of kinetic energy) when the test charge is allowed to be repelled.

In section 4-2, it was found that gravitational potential energy is gained when an object is moved against the earth's gravitational field. In Figure 4-3A, the surface of the earth could arbitrarily be allowed to represent zero potential. If the force F were to cause the one kilogram weight to be raised a distance of one meter, work would be performed on the weight and it

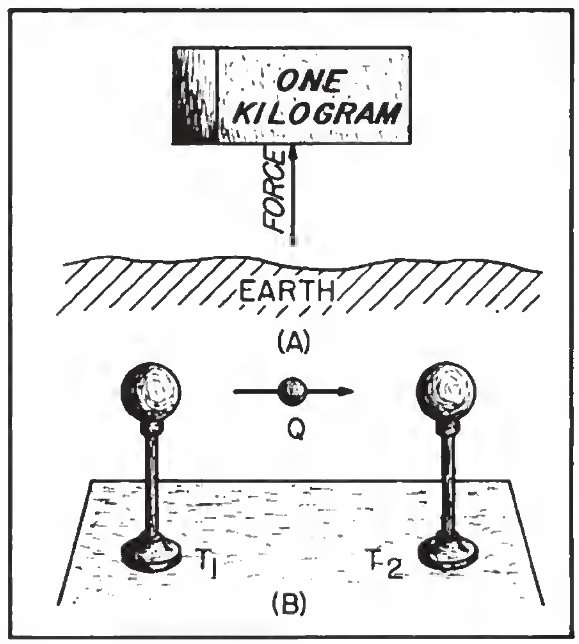


Figure 4-3 - Comparison between gravitational and electrical potential.

would now contain gravitational potential. Since a one kilogram mass exerts a force of 9.8 newtons as a result of gravity, this gravitational potential may be calculated as follows:

$$W = Fd \qquad (4\text{-}1)$$

$$W = (1\ \text{kgf})(9.8\ \text{n/kgf})(1\ \text{m})$$

$$W = 9.8\ \text{joules}$$

Gravitational potential energy is expressed

as joules per kilogram (for which no unit has been devised), therefore, the weight in Figure 4-3A has gained 9.8 joules of potential energy with respect to ground (earth).

A similar situation also exists for the electrical system represented in Figure 4-3B. If a quantity of charge is to be moved from terminal T_1 to terminal T_2 against an electrical force, work must be done on the charge and the charge will gain potential energy. In an electrical system, the electric potential is expressed as joules per coulomb and represents work (joules) per unit charge (coulombs). A potential of one joule per coulomb is called one VOLT in honor of Alessandro Volta who discovered one of the first practical methods of generating a continuous electrical potential. The symbol used for the volt is the letter E. If the joules of work and the coulombs of charge are known, the potential (E) in volts can be calculated by the following formula:

$$E = \frac{\text{joules}}{\text{coulombs}}$$

$$E = \frac{W}{Q} \qquad (4\text{-}3)$$

In Figure 4-3, if three coulombs of charge are moved from T_1 to T_2, and 180 joules of work are expended, the voltage at T_2 would be:

$$E = \frac{W}{Q} \qquad (4\text{-}3)$$

$$E = \frac{180}{3}$$

$$E = 60 \text{ volts}$$

This indicates that the potential at T_2 differs from the potential of T_1 by 60 volts, or that there is an ELECTRICAL POTENTIAL DIFFERENCE between T_2 and T_1 of 60 volts.

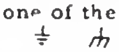
4-9. Polarity of Potential

In the discussion of section 4-8, nothing was said about the polarity of the potential developed by the movement of charges from T_1 to T_2. Assuming that the charges were positive, T_2 would become 60 volts positive with respect to T_1. In many sources of potential the charges to be moved are electrons. If this were the case in Figure 4-3B, the charge deposited on terminal T_2 would be negative. As a result, T_2 would be 60 volts negative with respect to T_1.

Q6. In the preceding example, where terminal T_2 is considered to be 60 volts negative with respect to T_1, would it be correct to say that T_1 is positive? Explain.

4-10. Symbols and Terms

In the previous sections the concept of a difference of potential was developed. In most electronic circuits only the difference of potential between two points is of importance and the absolute potentials of the points are of little concern. Very often it is convenient to use one standard reference for all of the various potentials throughout a piece of equipment. For this reason, the potentials at various points in a circuit are generally measured with respect to the metal chassis on which all parts of the circuit are mounted. The chassis is considered to be at zero potential and all other potentials are either positive or negative with respect to the chassis. When used as the reference point the chassis is said to be at GROUND POTENTIAL. Ground reference, abbreviated GND, is usually represented by one of the following symbols:



Occasionally rather large values of voltage may be encountered in which case the volt becomes too small a unit for convenience. In a situation of this nature, the kilovolt (Kv) meaning 1,000 volts is frequently used. As an example, 20,000 volts would be written as 20 Kv. In other cases the volt may be too large a unit, as when dealing with very small voltages. For this purpose the millivolt (mv), meaning one thousandth of a volt and the microvolt (uv) meaning one millionth of a volt are used. For example .001 volt would be written 1 mv and .000025 volts would be written as 25 uv.

In the everyday language of electronics the number of volts between two points is expressed in several different ways, some of which are: voltage, potential, potential difference, and electromotive force (EMF). Strictly speaking, each of these terms indicates a specific quantity, however, they are quite frequently used interchangeably. EMF for example, should only be used when referring to the force which causes charges to move through a source of voltage. The following sections will be devoted to the study of devices used to develop an electromotive force.

Q7. Express the following in more simple terms: (a) 250,000 volts, (b) 25,000,000 microvolts, (c) .001 millivolts.

GENERATION OF EMF

4-11. The Voltage Source

It has been shown that a concentration of charge develops a difference of potential (measured in volts) between it and some reference. Under certain conditions, this difference of potential is capable of accomplishing work. The

A5. Yes, however, the charge would be doing work rather than having the work done on it.

A6. Yes. T_1 would be considered to be positive providing T_2 is used as the reference point.

A7. (a) 250 kv, (b) 25v, (c) 1 uv.

object of the remainder of this chapter therefore, is to examine the various methods by which a difference of potential or voltage may be generated. In Chapter 2, it was demonstrated that a charge could be produced on a rubber rod by rubbing the rod with cat's fur. Due to the friction involved, the rubber rod assumes a negative potential and the fur becomes positive. Although it was not stated at that time, these quantities of opposite charge constitute a difference of potential between the rod and the fur. The electrons comprising this difference of potential are capable of doing work if a discharge is permitted to occur.

To be a practical source of voltage, the potential difference must not be allowed to dissipate, but must continuously be maintained. As one electron leaves the concentration of negative charge, another must be immediately provided to take its place or the charge will eventually diminish to the point where no further work can be accomplished. A VOLTAGE SOURCE therefore, is a device which is capable of supplying and maintaining voltage while some type of electrical apparatus is connected to its terminals. The internal action of the source is such that electrons are continuously removed from one terminal which becomes positive, and simultaneously supplied to the second terminal which assumes a negative charge.

Electromotive force is that force which moves charges within a voltage source. This name is misleading, however, because electromotive force cannot be measured in the conventional force units of newtons or pounds but is measured in volts. Thus, potential difference and electromotive force (EMF) are both measured in volts even though they are slightly different quantities and may have different values in a given source.

4-12. Generation by Friction

The first method discovered for creating a voltage was that of generation by friction. The development of charges by rubbing a rod with fur is a prime example of the way in which a voltage is generated by friction. Due to the nature of the materials with which this voltage is generated, it cannot be conveniently used nor maintained. For this reason, very little practical use has been found for voltages generated by this method.

In the search for methods to produce voltages of a larger magnitude and a more practical nature, machines were developed in which charges were transferred from one terminal to another by means of rotating glass discs or moving belts. Because the charges were obtained by induction rather than by friction, these devices were called INFLUENCE MACHINES. The most notable of these machines is the Van de Graaff generator. It is used today to produce potentials in the order of millions of volts for nuclear research. As these machines have little value outside the field of research, their theory of operation will not be described here.

Q8. What is the purpose of the length of metal chain that is dragged by a gasoline truck?

4-13. Generation by Pressure

Nearly all known inorganic (non-living) solids are crystalline in nature. For example, an examination of table salt under a magnifying glass shows the small grains as tiny cubes of salt. Each of these cubes has a precise atomic structure and constitute a single crystal of salt. Like many less common crystals, the salt crystal contains an equal number of positive and negative ions and is therefore electrically neutral. A crystal constructed of ions is called an ionic crystal.

One specialized method of generating an EMF utilizes the characteristics of certain ionic crystals such as quartz, Rochelle salts, and tourmaline. These crystals have the remarkable ability to generate a voltage whenever stresses are applied to their surfaces. Thus, if a crystal of quartz is squeezed, charges of opposite polarity will appear on two opposite surfaces of the crystal. If the force is reversed and the crystal is stretched, charges will again appear but will be of the opposite polarity from those produced by squeezing. If a crystal of this type is given a vibratory motion, it will produce a voltage of reversing polarity between two of its sides. Quartz or similar crystals can thus be used to convert mechanical energy into electrical energy. This phenomenon is called the PIEZOELECTRIC EFFECT. Crystals of this type also possess another interesting property, the "converse piezoelectric effect". That is, they have the ability to convert electrical energy into mechanical energy. A voltage impressed across the proper surfaces of the crystal will cause it to expand or contract its surfaces in response to the voltage applied.

The piezoelectric effect is believed to be the

result of a displacement of charge centers within the crystal as a result of mechanical stress. Figure 4-4 shows a two-dimensional cross-section of a crystal lattice. Notice that in this configuration the crystal is made up of equal numbers of positive and negative ions arranged in equilateral triangles of like charged bodies. (See Figure 4-4A).

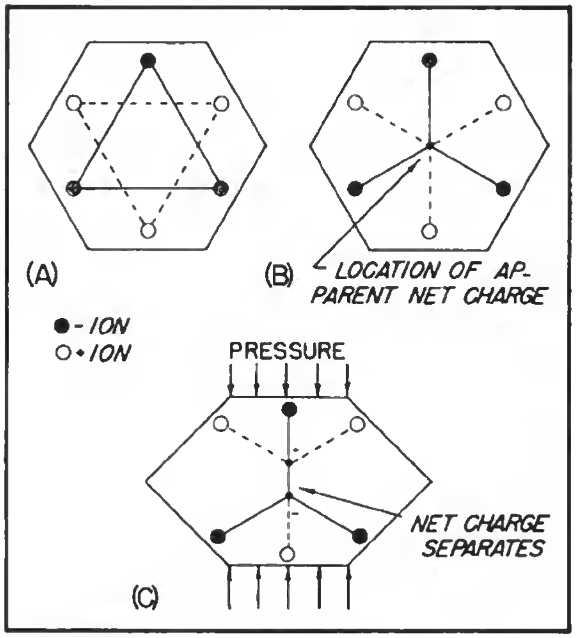


Figure 4-4 - Two dimensional Lattice

The net charge of each group of three similar charges appears to be located in the geometric center of this triangle as shown in part (B) of the diagram. Notice that the centers of net negative and net positive charges coincide when no mechanical stress is applied to the crystal.

If sufficient pressure is now applied to the top and bottom surfaces of the crystal, the ions within the crystal are forced to move. This movement results when each triangle of charges is compressed in a vertical direction and spread outward in a lateral direction. As the shape of each triangle changes, the location of the apparent net charges will also change. The location of the net positive charge will move upward and the location of the net negative charge will move downward as shown in Figure 4-4C. Since the two centers of unlike charge are no longer coincident a difference of potential exists within the crystal. Adjacent crystal sections likewise produce an EMF of a corresponding polarity which combine to develop voltage potential on the surfaces of the crystal. In this illustration the top surface takes on a positive charge while the bottom surface becomes negative. In this type of crystal the potential is developed between the surfaces to which the pressure is applied. In other crystals, the potential can develop in the direction of stress or at right angles to the direction of stress, depending on which surfaces receive the stress. In still other ionic crystals, no piezoelectric effect is observed.

Some of the common devices that make use of piezoelectric crystals are microphones, phonograph cartridges, and oscillators used in radio transmitters, radio receivers, and sonar equipment.

This method of generating an EMF is not suitable for applications having large voltage or power requirements but is widely used in sound and communications systems where small signal voltages can be effectively utilized.

Q9. Can a "non-ionic" crystal such as silicon be utilized as a piezoelectric crystal?

4-14. Generation by Heat

From the discussion of conductors and insulators in Chapter 1, it has been shown that materials contain quantities of free electrons within their atomic structure. The number of free electrons is dependent upon the crystal lattice structure of the material. The better the conductor the greater the quantity of free electrons.

It has been discovered that when two dissimilar conductive materials are brought into physical contact with each other there is a movement of free electrons from the more dense material to the less dense material. This action results in a deficiency of electrons in one material and an excess in the other. The less dense material, therefore, receives an excess of negative ions which causes the material to become negatively charged with respect to the other material which assumes a positive charge. This action is illustrated by the diagrams in Figure 4-5.

Note that an electrical potential difference is established between the two metals due to the displacement of electrons and their relative positions. This potential difference is known as CONTACT POTENTIAL DIFFERENCE. The addition of heat to the metals agitates their lattice structures and causes an increase in the transfer of free electrons. At a fixed temperature, however, the transfer of electrons soon reaches a static condition and ceases further movement.

In 1821, Thomas Johann Seebeck discovered that an EMF could be produced by purely thermal means in a circuit composed of two dissimilar conductors when their junctions are kept at

A8. The chain forms a discharge path for the voltage generated between the truck and the earth due to friction of the tires on the pavement.

A9. No. They do not possess the necessary positive and negative ions needed to produce the piezoelectric effect.

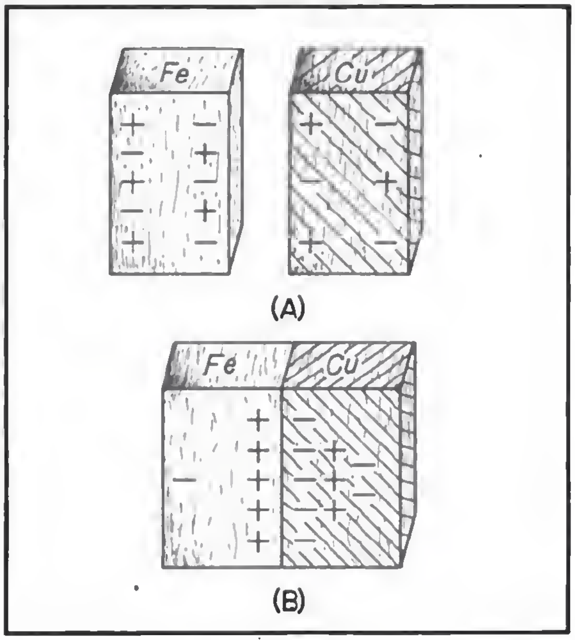


Figure 4-5 - Transfer of free electrons between dissimilar conductive materials.

different temperatures. This form of producing an electrical potential is called THERMOCOUPLE EFFECT. The device which works on this principle is called a THERMOCOUPLE. The EMF in the circuit is known as a THERMAL EMF.

A thermocouple circuit, such as shown in Figure 4-6, provides a means for continuous replenishment of electrons from the material that gains the abundance of electrons to the material that becomes deficient in electrons. The direction of electron movement and the magnitude of the potential difference between the metals depends upon the type of metals used and the difference in temperature between their junctions.

A thermocouple of chromel-alumel will develop approximately 50 millivolts of electrical potential difference between the metals when one junction is at 0° C and the other at 1200° C. Obviously this method of generating an EMF is not practical for producing source voltages for circuits required to perform an appreciable

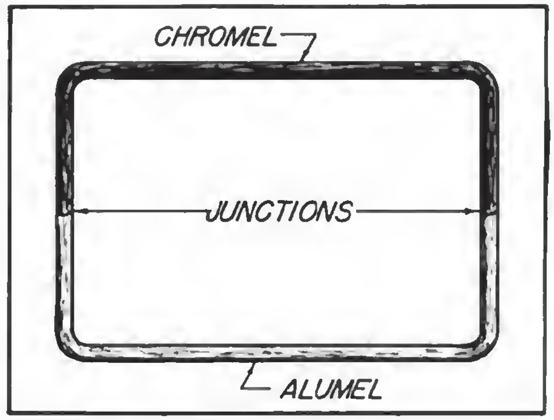


Figure 4-6 - A thermocouple circuit.

amount of work. Due to its sensitivity to temperature changes, however, the thermocouple is widely used for temperature measurement and temperature control devices.

Q10. Can a thermocouple be constructed of three dissimilar metals?

4-15. Generation by Light

In 1905, Albert Einstein developed the theory that a beam of light consists of small bundles of energy called LIGHT QUANTA or PHOTONS. This theory was so radical compared to other contemporary theories concerning light energy that it was not generally accepted until 1916 after additional experiments by an American physicist, Robert Millikan, added support. The energy of a photon was found to be proportional to the frequency or color of the light. If a photon collides with an electron at or near the surface of a metal, it may transfer its energy to the electron.

Subsequent experiments by J. J. Thompson proved that light energy falling on the surface of a metal such as zinc would cause electrons to be forced out of the metal. As the electrons leave the surface of the zinc it becomes deficient in electrons and thus assumes a positive charge. This phenomenon is known as the PHOTOELECTRIC EFFECT. By properly combining layers of metal, a PHOTOELECTRIC CELL can be constructed in which light energy is used to generate an EMF.

The construction of a typical photoelectric cell is shown in Figure 4-7. The cell consists of an iron base plate on which is placed a coating of selenium. Next a layer of material is placed over the selenium which will allow the passage of electrons in one direction only. A thin transparent film of gold or silver is then

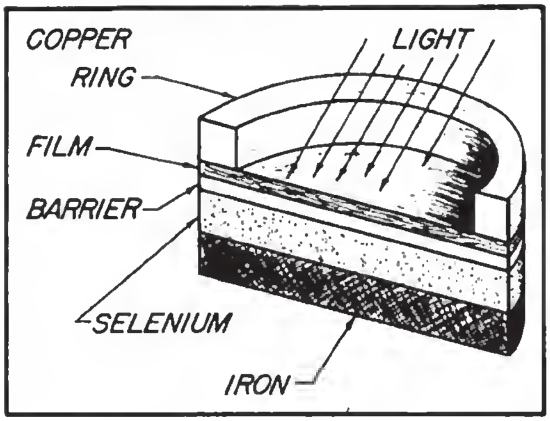


Figure 4-7 - Photoelectric cell.

formed on top of this one-way or barrier layer. Finally, a copper ring is pressed against the gold or silver film so that electrical connection can be made to the film.

When light energy falls on the cell it travels through the film and the barrier layer and strikes the light sensitive selenium. The selenium then emits electrons which travel through the barrier and collect on the metallic film. The film thus acquires a negative charge while the selenium and the back-plate become positively charged. Due to the one way characteristic of the barrier, the electrons cannot return to the selenium and neutralize the charge. As a result, the iron back-plate remains positive and the copper collector ring is negative.

If a meter is connected to this cell it will indicate light intensity and can be used as a photographers light meter. The solar batteries used to supply power to space vehicles is another application of the photoelectric effect.

Q11. What determines the energy with which the electrons in a photocell are emitted?

Q12. What determines the number of electrons emitted?

4-16. Generation by Magnetism

One of the most widely used methods of generating an EMF is that of generation by ELECTROMAGNETIC INDUCTION. In this process an electromotive force is caused to exist in a conductor by the interaction of the conductor with a magnetic field of force. Figure 4-8 shows a length of copper conductor as it is passed through the poles of a horseshoe magnet. As the conductor passes between the poles of the magnet it must travel through the field of force between the poles. This field is represented by lines of force shown leaving the north pole and entering the south pole of the magnet. Thus, as the conductor moves through the field it "cuts" the lines of force.

In Chapter 1 it was pointed out that a conductor has many free electrons. These electrons are not firmly attached to any particular atom, but are free to wander about within the conductor. If the conductor is made to move, it carries these free electrons along with it, causing the electrons to move at the same speed and in the same direction as the conductor. Thus, as the conductor in Figure 4-8 moves through the magnetic field, the free electron which it contains moves with it.

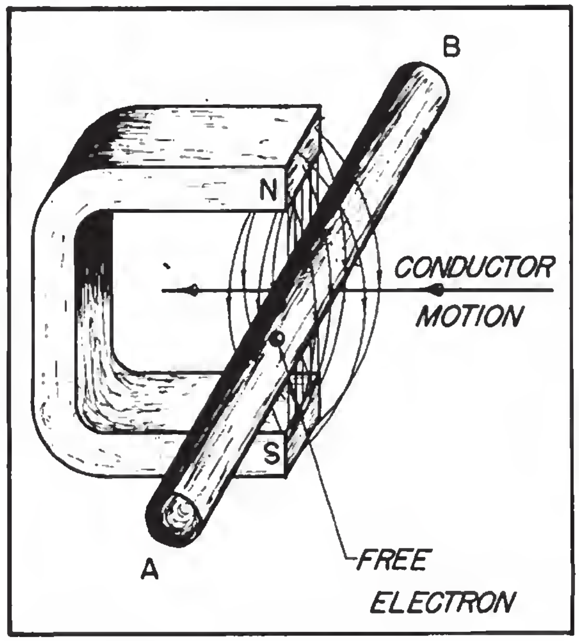


Figure 4-8 - Motion of electron and conductor.

Q13. What three factors determine the number of lines of force cut per unit time in Figure 4-8?

Q14. Would any lines of force be cut if the magnet were to be moved instead of the conductor?

Whenever an electron moves, it generates a magnetic field whose lines of force appear as concentric circles about the electron as illustrated in Figure 4-9. To determine the direction of the field encircling the electron, visualize the left hand placed around the electron as shown in Figure 4-9, with the thumb pointing in the direction in which the electron is traveling. The curled fingers then point in the direction of the magnetic field about the electron (see Figure 4-9). The direction of this field is

A10. Yes. Two of the junctions must be maintained at the reference temperature and the third junction can be used at the test junction.

A11. Color of light.

A12. The light intensity.

A13. (1) The strength of the magnetic field
(2) the angle (with respect to the field) of motion of the conductor
(3) the speed of the conductor

A14. Yes.

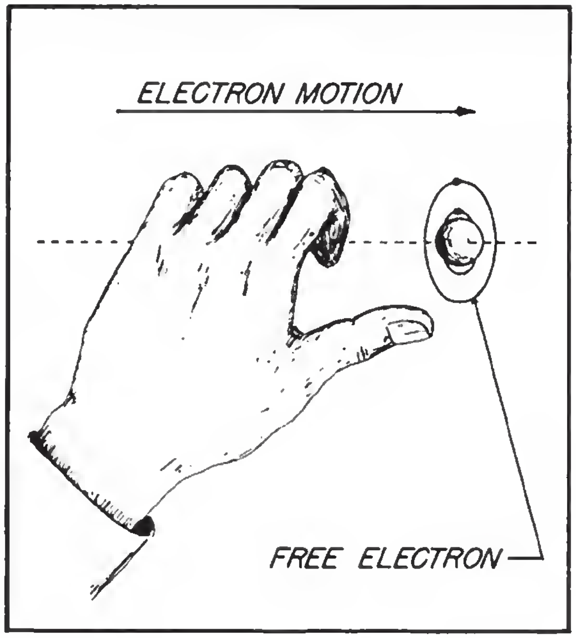


Figure 4-9 - Field about moving electron.

shown by the arrow heads on the lines of force encircling the electron.

In Figure 4-10, the lines of force about the electron are shown as the electron enters the field between the poles of a magnet. As shown in the diagram, the lines about the electron will be traveling in the same direction on the left-hand side of the electron, and in opposite directions on the right-hand side of the electron.

It was stated in Chapter 3 that lines of force traveling in the same direction repel one another, and that lines traveling in opposite directions attract. This being true, the two sets of lines on the left-hand side of the electron (Figure 4-10) will repel each other while those on the right will attract. This action will produce a force on the electron directed to the right of the diagram.

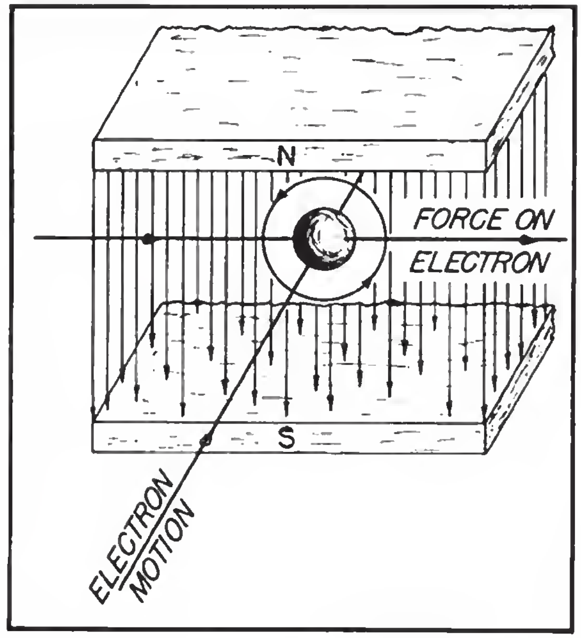


Figure 4-10 - Interaction of fields.

Since the electron is "free" to move within the conductor, it will be forced to the end of the conductor labeled B in Figure 4-8. As all electrons are similar, all free electrons in the conductor will have a tendency to move from A to B as the conductor is moved between the poles of the magnet.

The net result of the movement of the conductor into the field of the magnet, is the forced or directed migration of millions of electrons through the conductor from A to B as illustrated in Figure 4-11. The electrons, therefore, are repelled from the A end of the conductor and will accumulate at the B end creating a difference of potential between these two points. This process of generating a voltage is called ELECTROMAGNETIC INDUCTION, and the voltage generated is called an INDUCED voltage. The majority of the world's commercial electric power is produced by this method.

Q15. What would happen to the free electrons in the conductor if its motion through a magnetic field were suddenly stopped?

Q16. What would happen to the electrons if the direction of motion of the conductor through a magnetic field were reversed?

The amount of voltage induced in a conductor cutting a field of force is dependent on three factors which are: (1) the strength of the

magnetic field (2) the speed at which the conductor cuts the field (3) the length of the conductor within the field.

Referring back to Coulomb's law of magnetic force (section 3-9) it was stated that the force between two magnetic poles is directly proportional to the strength of the poles. This being the case a stronger magnetic field between the poles of the magnet would cause a greater force to be exerted on the free electrons in the conductor and impart more energy to them.

If the speed of the conductor is increased, the electrons within the conductor move at a higher velocity producing a stronger magnetic field. As before the stronger field of force imparts more energy to the electron. Since a volt was defined as a joule of energy per coulomb, the greater the energy supplied to the electron, the greater will be the induced voltage.

The length of the conductor has a direct bearing on the magnitude of induced voltage. The voltages induced in each tiny section of the wire are additive. Thus, a long conductor may be considered to consist of a large number of sections and therefore contain a large total voltage across its length.

The ability to easily generate a voltage by magnetic induction has enabled man to economically produce immense quantities of electrical power. The availability of this power has been vitally responsible for our present high standard of living and unprecedented scientific achievement. The basic construction and operation of the devices used to generate electricity by electromagnetic induction is shown in detail in Chapter 8.

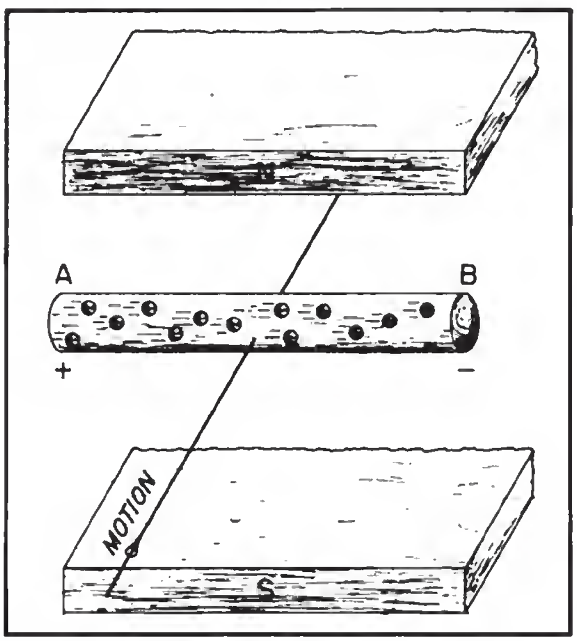


Figure 4-11 - Electron displacement within a conductor.

CELLS AND BATTERIES

4-17. Generation by Chemical Action

An EMF may be generated by the energy liberated as a result of chemical reactions. In this process, chemical energy is converted into electrical energy in a device called a VOLTAIC CELL.

It is said that the discovery of the voltaic cell was brought about by an unusual event which occurred during an anatomy demonstration prepared by Luigi Galvani, an 18th century Italian physicist. Part of the apparatus for the experiment consisted of a pair of frog's legs which Galvani had removed from a brine solution and suspended by a copper wire. During the course of the demonstration, Galvani noticed that every time he touched both the frog and the copper wire with an iron scalpel, the legs jerked convulsively. He wrongly concluded that electricity was being produced by the muscles of the frog legs.

A short time later an Italian scientist, Allessandro Volta, discovered the true source of the electricity. He found it to be the result of a chemical reaction occurring between the copper, iron, and brine solution used in the experiment. By further extending his investigation he succeeded in constructing the first electric battery called a VOLTAIC PILE.

4-18. The Voltaic Cell

In its simplest form, a voltaic cell consists of two unlike pieces of metal called ELECTRODES, which are immersed in either a salt or an acid solution called an ELECTROLYTE. As a chemical reaction occurs between the two electrodes and the electrolyte, opposite charges accumulate on the two electrodes. Any two unlike metals can be used for the electrodes as long as the electrolyte will react chemically with the electrode material. Because the amount of voltage developed, and the life expectancy of the cell are dependent on the combination of materials used, certain materials are preferred. Since the internal action of the various types of cells are similar, the following explanation may be taken as typical of cells in general.

The construction of a simple voltaic cell is illustrated pictorially in Figure 4-12, which shows a glass jar filled with a solution of sulfuric acid and water. As the acid dissolves in the water, ionization occurs. The sulfuric acid dissociates into hydrogen ions (H^+) having a single positive charge and sulphate ions (SO_4^{--}) carrying two negative charges (see Figure 4-13).

A15. They would discontinue their directed motion and drift haphazardly within the conductor.

A16. The direction of movement of the electrons would reverse.

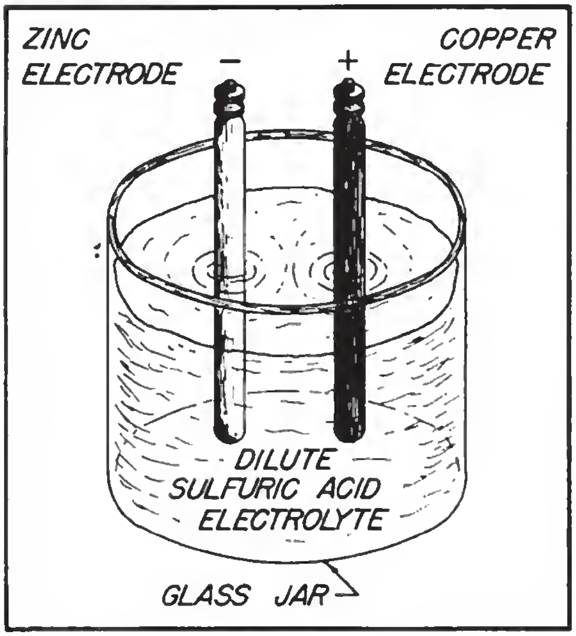


Figure 4-12 - Voltaic cell.

If a zinc bar is placed into the solution, the acid in the electrolyte will react with the zinc causing some of it to dissolve. In dissolving, zinc ions containing two positive charge (Z_n^{++}) leave the electrode and pass into the electrolyte. Each zinc ion that goes into the solution leaves two electrons behind, causing a negative charge to accumulate on the zinc electrode. As the zinc electrode becomes negative, it attracts the positive ions in the solution, and some of them return to the electrode. In a short time equilibrium is established and the rate of loss of ions from the zinc is equal to the rate of return. The zinc electrode thus remains negative and a cloud of positive ions forms in the electrolyte.

When a copper bar is immersed in the solution some of the positive hydrogen ions (H^+) come in contact with the surface of the copper. Each positive ion then pulls one of the many free electrons out of the copper and becomes a neutral atom of hydrogen gas. The copper electrode, which has given up its electrons to the hydrogen ions, accumulates a positive charge.

As a consequence of the above chemical action, the zinc electrode becomes negative and the copper electrode becomes positive. A

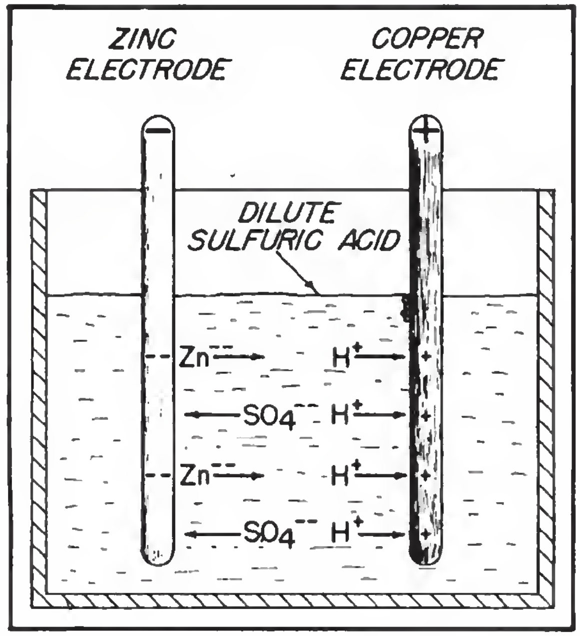


Figure 4-13 - Formation of ions.

difference of potential therefore exists between the two electrode terminals, and the cell is capable of supplying electrical energy to an external electrical device. A voltaic cell constructed with copper and zinc electrodes will develop a potential between the terminals of about 1.08 volts.

Q17. Can the voltage output of a voltaic cell be increased by using larger electrodes or more electrolyte?

A cell, in the process of delivering electrical energy to an external device, is said to be DISCHARGING. To study the action as a cell discharges, the arrangement shown in Figure 4-14 will be used.

In order for a cell to discharge, an external path must be provided through which the excess electrons accumulated on the negative terminal can flow to the positive terminal. In Figure 4-14 this path is provided by two conducting wires and an electric lamp. Once a complete path is established between the terminals of the cell, some of the excess electrons of the zinc will leave the negative terminal and flow through the conductor and lamp to the positive terminal of the cell. The act of releasing some of the excess electrons on the zinc upsets the equilibrium which had originally been established between the positive Zn^{++} ions in the electrolyte and the negative electrons on the zinc electrode. This permits more zinc ions to dissolve into

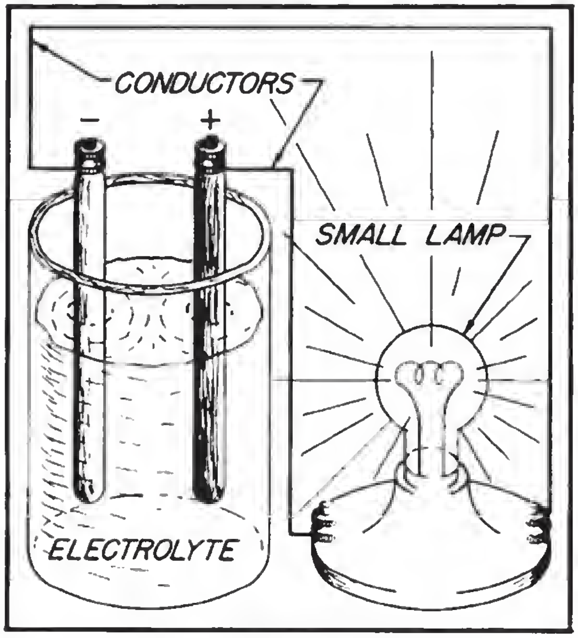


Figure 4-14 - Discharging a cell.

the electrolyte. On the average, a zinc ion will dissolve into the electrolyte for each two electrons which leave the negative terminal. As a result of this chemical action, the zinc terminal is continuously supplied with electrons.

While all this is happening at the negative terminal, a similar sequence of events is taking place at the positive terminal. The electrons arriving at the positive terminal of the cell reduce the positive charge on the copper electrode. This allows more positive hydrogen ions to approach the copper and extract electrons from its surface. Thus, at the positive electrode as well as the negative, the chemical action maintains a constant supply of charge.

The eventual result of discharging a cell of this type is destruction of the cell. As noted above, the zinc electrode is dissolved or consumed as the cell is used. The Zn^{++} ions that go into the electrolyte solution combine with the sulphate ions (SO_4^{--}) to form zinc sulphate. This process is non-reversible and therefore the cell cannot be recharged or restored to its original condition. A cell that cannot be recharged is known as a PRIMARY CELL.

4-19. Polarization

During the discussion of the chemical action that occurs at the positive terminal of a cell, it was mentioned that the hydrogen ions were converted into hydrogen gas by extracting electrons from the copper electrode. Some of this gas will rise to the surface of the electrolyte and escape into the atmosphere as free hydrogen gas. A large portion of the gas, however, will form bubbles and cling to the surface of the copper electrode. If a sufficient amount of gas is generated, a layer of hydrogen forms over the surface of the metal. This layer of gas covers the contact area of the electrolyte around the copper electrode and reduces the transfer of electrons from the copper to the hydrogen ions in the electrolyte. In extreme cases, the gas may completely insulate the electrode from the electrolyte and prevent the cell from delivering a continous supply of electrons to whatever may be connected to its terminals. The process of forming this layer of gas is called POLARIZATION.

If the bubbles of hydrogen gas are wiped from the copper electrode and the electrode is placed back into the electrolyte, the cell will again function normally until polarization once more halts the action of the cell. Since continual wiping of the electrode is neither convenient nor practical, some automatic means must be employed for the removal of the bubbles. This is usually done by placing a chemical substance into the cell which will react with the hydrogen and dissolve the gas. If a substance rich in oxygen, such as manganese dioxide, is placed into the cell the oxygen from the manganese dioxide will combine with the hydrogen to form water. If the hydrogen can be converted to water as fast as it forms, the cell will be free from polarization and will operate normally. A substance used to counteract polarization is called a DEPOLARIZING AGENT.

4-20. Local Action

When there is no external circuit connected to the terminals of the cell, electrons cease to flow, theoretically stopping all chemical action within the cell. If this were true, a cell would last indefinitely if not used. However, commercial zinc contains many impurities, such as iron, carbon, lead, and others. These impurities imbedded in the zinc form many small cells within the zinc electrode and permit a flow of electrons between the impurity and the zinc. The flow of electrons allows zinc ions to dissolve into the electrolyte, just as they do when the cell is operating normally. This wasting away of the zinc when the cell is not in use is called LOCAL ACTION.

Local action could be entirely prevented by fabricating the zinc electrode from pure zinc. This is not feasible from an economic standpoint, however, since the cost of such a process would be prohibitive. A more practical method of minimizing local action is by AMALGAMATION, a process wherein the zine is treated with mercury. By the amalgamation process, the

A17. No.

zinc containing the impurities is completely coated with a thin layer of mercury. Due to the chemical characteristics of mercury, only the zinc ions can readily dissolve and pass through the mercury into the electrolyte. Nearly all of the impurity atoms remain covered beneath the mercury and are unable to react with the sulfuric acid. Since practically no electrolyte touches the impurity atoms, local action is greatly reduced, and the life of the cell is considerably lengthened.

Q18. What determines the rate at which the zinc terminal is consumed? (Excluding local action)

4-21. The Dry Cell

Although the original voltaic cell was the first practical source of electrical energy, necessity has brought about the evolution of a variety of different types of cells. One of these is the DRY CELL, so called because the electrolyte is in the form of a paste rather than a liquid. It must be emphasized that the electrolyte in this cell is not really dry, for if it were no ions could move through the electrolyte to produce charges at the electrodes. The dry cell has a distinct advantage over the wet voltaic cell in that it may be used in any position without spilling the electrolyte. The dry cell to be described has an EMF of approximately 1.5 volts.

The construction of a common type of dry cell is shown in Figure 4-15 (cutaway view of a dry cell).

The internal parts of the cell are located in a cylindrical zinc container. This zinc container serves as the cell's negative electrode. The container is lined with a non-conducting material, such as blotting paper, to insulate the zinc from the paste electrolyte. A carbon electrode is located in the center and serves as the positive terminal of the cell. The paste is a mixture of several substances. Its composition may vary, depending on the manufacturer of the cell. Generally, the paste will contain some combination of the following substances: ammonium chloride (sal ammoniac), powdered coke, ground carbon, manganese dioxide, zinc chloride, graphite or water.

This paste, which is packed in the space between the carbon and the blotting paper, also serves to hold the carbon electrode rigid in the center of the cell. When packing the paste in the cell, a small expansion space is left at the top. The cell is then sealed with asphalt-saturated cardboard.

Binding posts are attached to the electrodes so that wires may be conveniently connected to the cell.

Since the zinc container is one of the electrodes, it must be protected with some insulating material. Therefore, it is common practice for the manufacturer to enclose the cells in cardboard containers.

The dry cell (Figure 4-15) is fundamentally the same as the simple voltaic (wet cell) described earlier as far as its internal action is concerned. The action of the water and the ammonium chloride in the paste, together with the zinc and carbon electrodes, produces the voltage of the cell. Manganese dioxide is added to reduce polarization due to hydrogen gas and zinc chloride to reduce the polarization due to ammonia. The blotting paper serves two purposes, one being to keep the paste from making actual contact with the zinc container and the other being to permit the electrolyte to filter through to the zinc slowly. The cell is sealed at the top to keep air from entering and drying the electrolyte. Care should be taken to prevent breaking this seal.

A cell that is not put into use (sits on a storage shelf) will gradually deteriorate because of slow internal chemical actions (local action) and changes in moisture content. However, this deterioration is usually very slow if cells are properly stored. High-grade cells of the larger sizes, such as the standard No. 6 should have a shelf life of a year or more. Smaller size cells have a proportionately shorter shelf life, ranging down to a few months for the very small size. If unused cells are stored in a cool place, their shelf life will be greatly increased.

THE LEAD-ACID CELL

4-22. Secondary Cells

SECONDARY CELLS function on the same basic chemical principles as primary cells. They differ mainly in that they may be recharged, whereas the primary cell is not rechargable. Some of the materials of a primary cell are consumed in the process of changing chemical energy to electrical energy. In the secondary cell, the materials are converted from one form to another as the cell discharges. Discharged secondary cells may be restored (charged) to their original state by forcing an electric current from some other source through the cell in the opposite direction to that of discharge.

The STORAGE battery consists of a number of secondary cells connected in series. Properly speaking, this battery does not store electrical energy, but is a source of chemical energy which produces electrical energy. There are

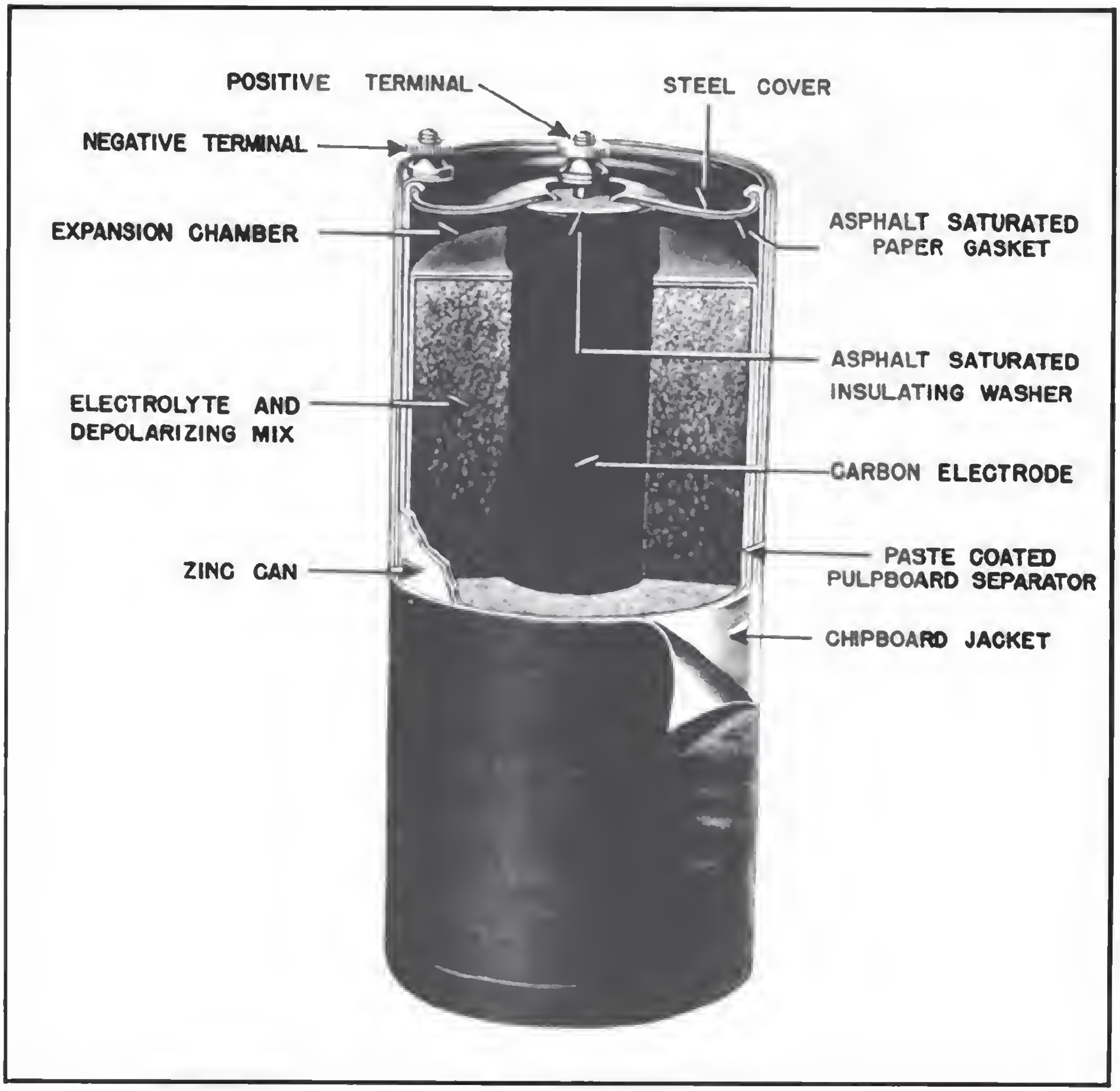


FIGURE 4-15 - Cutaway view of a dry cell.

three main types of storage cells, the lead-acid type, which has an EMF of 2.2 volts per cell; the nickel-iron-alkali type; and the nickel-cadmium-alkaline type. The latter two have an EMF of 1.2 volts per cell. Of these three types, the lead-acid is the most widely used, and will be the only one described.

In its charged condition, the active materials in the lead-acid battery are lead dioxide (sometimes referred to as lead peroxide) and spongy lead. The lead dioxide is used as the positive plate while the spongy lead forms the negative plate. The electrolyte is a mixture of sulfuric acid and water. The strength (acidity) of the electrolyte is measured in terms of its SPECIFIC GRAVITY. Specific gravity is the ratio of the weight of a given volume of electrolyte to an equal volume of pure water. Concentrated sulfuric acid has a specific gravity of about 1.830; pure water has a specific gravity of 1.000. The acid and water are mixed in a proportion to give the specific gravity desired. For example, an electrolyte with a specific gravity of 1.210 requires roughly one part of concentrated acid

A18. The rate at which charge is drawn from the cell.

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to four parts of water. As a storage battery discharges, the sulfuric acid is depleted and the electrolyte is gradually converted into water. This action provides a guide in determining the state of discharge of the lead-acid cell. The electrolyte that is usually placed in a lead-acid battery has a specific gravity of 1.350 or less. Generally, the specific gravity of the electrolyte in Navy portable batteries is adjusted between 1.210 and 1.220. On the other hand the specific gravity of the electrolyte in submarine batteries when charged is from 1.285 to 1.300.

In a fully charged battery the positive plates are pure lead dioxide and the negative plates are pure lead. Also, in a fully charged battery, all of the acid is in the electrolyte so that the specific gravity is at its maximum value. The active materials of both the positive and negative plates are porous, and have absorptive qualities similar to a sponge.

The pores of the plates are filled with the battery solution (electrolyte) in which they are immersed. As the battery discharges, the acid in contact with the plates separates from the electrolyte. It forms a chemical combination with the plate's active material, changing it to lead sulfate. Thus, as the discharge continues lead sulfate forms on the plates, and more acid is taken from the electrolyte. The water content of the electrolyte becomes progressively higher, that is, the ratio of water to acid increases. As a result, the specific gravity of the electrolyte will gradually decrease during discharge.

When the battery is being charged, the reverse action takes place. The acid held in the sulfated plate material is driven back into the electrolyte. When fully charged, the material of the positive plates is again pure lead dioxide and that of the negative plates is pure lead.

Electrical energy is derived from a cell when the plates react with the electrolyte. As a molecule of sulfuric acid separates, part of it combines with the spongy lead plates. It makes the spongy lead plates negative, and at the same time forms lead sulfate. The remainder of the sulfuric acid molecule, lacking electrons, has thus become a positive ion. The positive ions migrate through the electrolyte to the opposite (lead dioxide) plates and take electrons from them. This action makes the lead dioxide plates positive, and neutralizes the positive sulfuric acid ions. Lead sulfate and water is formed in the process.

In the charged condition the positive plate contains lead dioxide, PbO_2; the negative plate is composed of spongy lead, Pb; and the solution contains sulfuric acid, H_2SO_4. In the discharged condition both plates contain lead sulfate, $PbSO_4$, and the solution contains water, H_2O. As the discharge progresses, the acid content of the electrolyte becomes less and less, because it is used in forming lead sulfate, and the specific gravity of the electrolyte decreases. A point is reached where so much of the active material has been converted into lead sulfate that the cell can no longer produce sufficient current to be of practical value. At this point, the cell is said to be discharged. Since the amount of sulfuric acid combining with the plates at any time during discharge is in direct proportion to the ampere-hours (product of current in amperes and time in hours) of discharge, the specific gravity of the electrolyte is used as a guide in determining the state of discharge of the lead-acid cell.

If the discharged cell is properly connected to a direct-current source, the voltage of which is slightly higher than that of the cell, current will flow through the cell in the opposite direction to that of discharge and the cell is said to be CHARGING. The effect of the current will be to change the lead sulfate on both the positive and negative plates back to its original active form of lead dioxide and spongy lead, respectively. At the same time, the sulfate is restored to the electrolyte with the result that the specific gravity of the electrolyte increases. When all of the sulfate has been restored to the electrolyte, the specific gravity will again be maximum. The cell is then fully charged and is ready for use again.

It should always be remembered that the addition of sulfuric acid to a discharged lead-acid cell does not recharge the cell. Adding acid only increases the specific gravity of the electrolyte and does not convert the lead sulfate on the plates back into active material (spongy lead and lead dioxide) and consequently does not bring the cell back to a charged condition. To recharge a cell a charging current must be passed through the cell.

As a cell becomes nearly charged, hydrogen gas (H_2) is liberated at the negative plate and oxygen gas (O_2) is liberated at the positive plate. This action occurs because the charging current has become greater than the amount necessary to reduce the remaining amount of lead sulfate on the plates. Thus, the excess current ionizes the water in the electrolyte. This action is necessary to develop a full charge in the cell.

Hydrogen gas is highly explosive. NO open flame or smoking, should be allowed in the proximity of storage batteries.

4-23. Lead-Acid Cell Construction

Individual plates are formed into positive and negative groups. When these groups are assembled, they become a cell element (Figure 4-16). The number of negative plates is always one more than the number of positive plates so that both sides of each positive plate are acted upon chemically. The active material on the positive plates expands and contracts as the battery is charged and discharged. The expansion and contraction must be kept the same on both sides of the plate to prevent buckling.

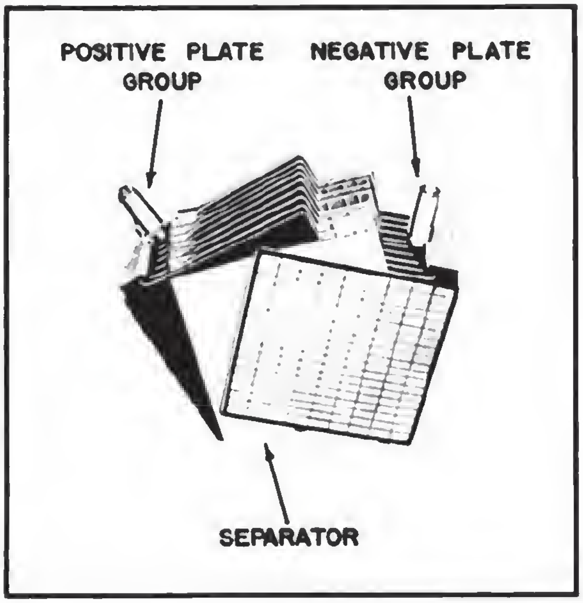

Figure 4-16 - Partly assembled cell element.

Separators of wood, rubber, or glass are placed between the positive and negative plates to act as insulators (Figure 4-16). These separators are grooved vertically on one side and are smooth on the other. The grooved side is placed next to the positive plate to permit free circulation of the electrolyte around the active material.

An assembled lead-acid cell with the positive and negative terminals projecting through the cell is shown in Figure 4-17. A hole fitted with a filler cap is provided in each cell cover to permit filling and testing. The filler cap has a vent hole to allow the gas that forms in the cell during charge to escape.

The ordinary 6-volt portable storage battery consists of 3 cells assembled in a molded hard rubber (monobloc) case. Metal cannot be used because of the acid electrolyte. Each cell is contained in an acidproof compartment within the case. The cells are connected in series by means of lead-alloy connectors that are attached to the terminal posts of adjacent cells by a lead-burning process. The space between the case and the edges of the cell covers is filled with an acidproof battery-sealing compound, or pitch. This compound is a blend of bituminous materials that are processed so that they remain solid at high temperatures.

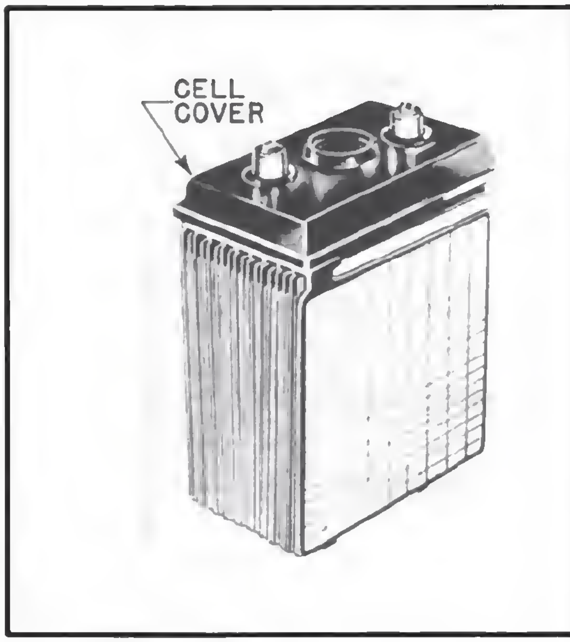

Figure 4-17 - Assembled lead-acid cell.

Figure 4-18 shows a cutaway view of a lead-acid cell and a battery.

4-24. Cell Connections

When an EMF is required that exceeds the amount developed by a single cell it is necessary to combine the potentials from more than one cell. A combination of cells connected together to produce an EMF is called a BATTERY. The cells may be connected in SERIES, PARALLEL or in a SERIES PARALLEL combination.

Cells arranged with the negative terminal of one connected to the positive terminal of another, and so on until all cells are thus connected, leaving the positive terminal of the first and the negative terminal of the last open (no connections), are connected in SERIES. Figure 4-19 shows a pictorial and a schematic representation of cells connected in series. The open terminals become the output terminals of the battery that is formed and are, therefore, the points to which a load device or voltage

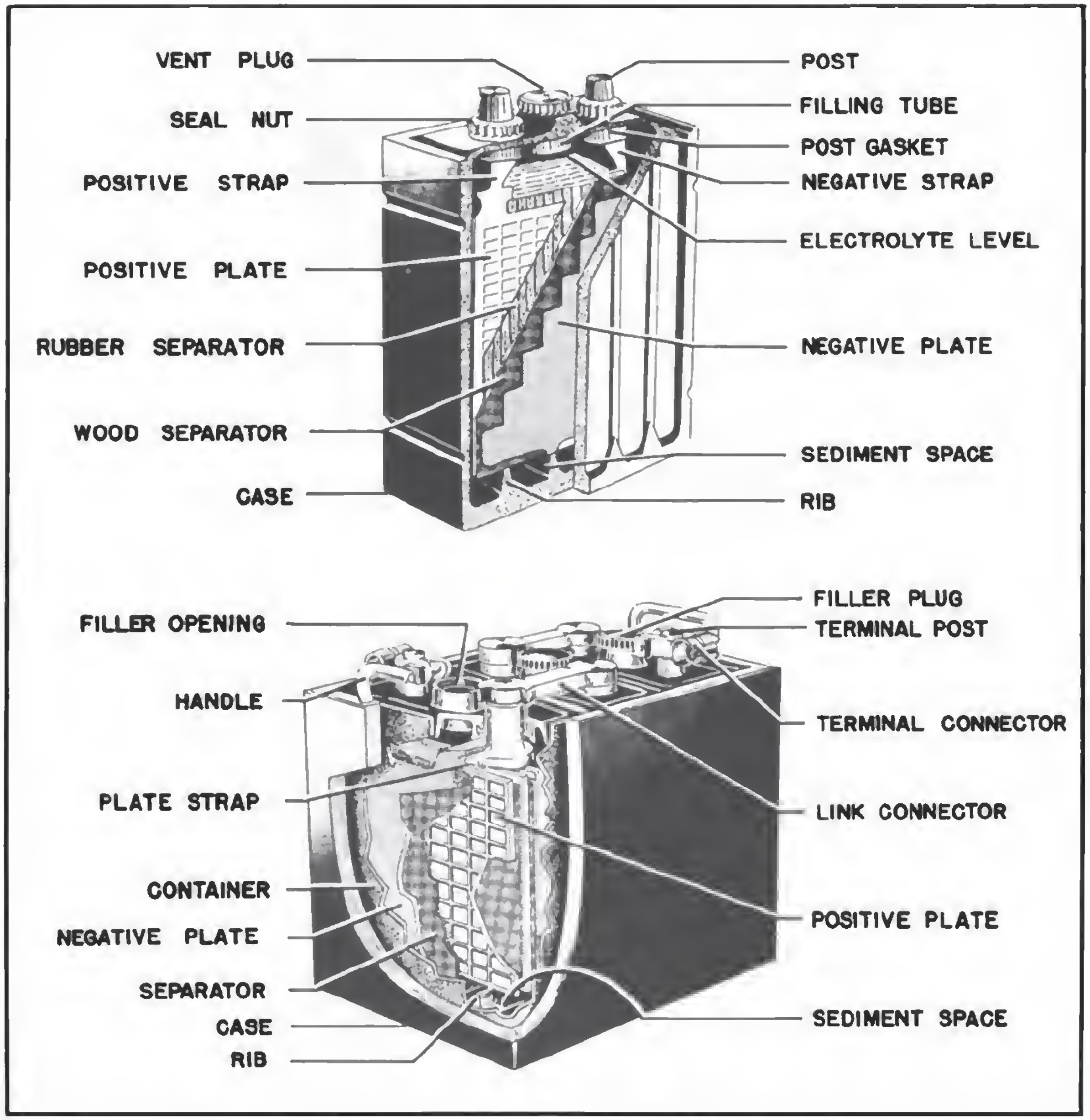

FIGURE 4-18 - Cutaway view of a lead-acid cell and battery.

measuring instrument is attached. When cells are connected in series, the total voltage is equal to the SUM of the voltages of the individual cells.

Figure 4-20 shows three cells connected in parallel. Note that all positive terminals are connected together and one of these terminals becomes the positive battery terminal. Likewise, all of the negative terminals are connected together one of which becomes the negative battery terminal. When cells are connected in parallel, the total voltage is equal to the voltage of ONE CELL. All cells connected in parallel should be of equal EMF. The advantage of the parallel connection of cells is increased work life of the battery. Whenever a battery is

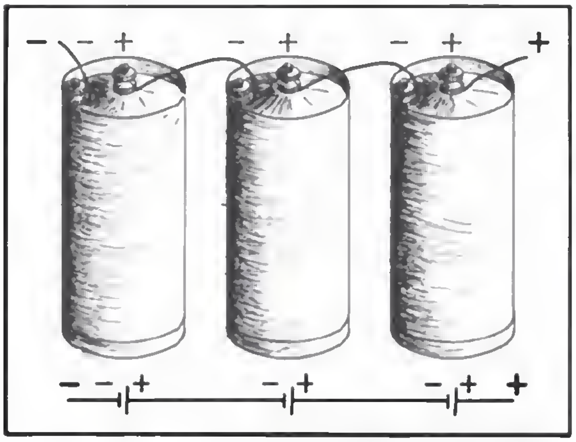

Figure 4-19 - Cells connected in series.

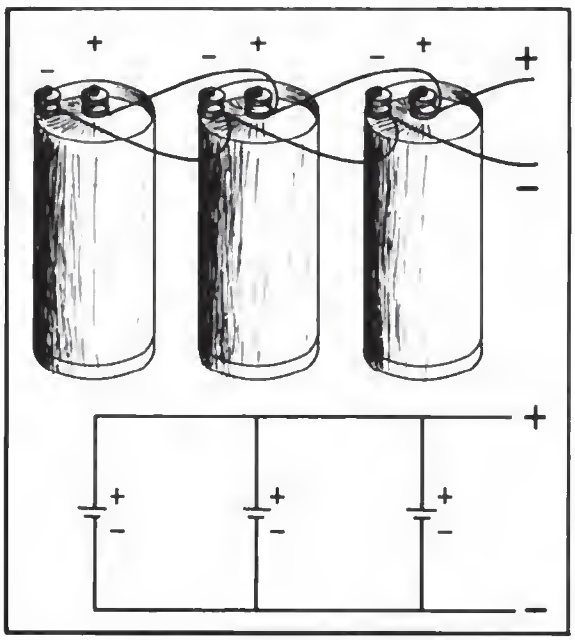

Figure 4-20 - Cells connected in parallel.

required with both a large potential and a long or heavy work producing capability, SERIES PARALLEL connections of cells are used. An example of series-parallel connected batteries is shown in Figure 4-21.

Q19. What polarity is the center terminal of a dry cell?

Q20. What is the output voltage of a battery containing five cells of 1.5 volts each connected in parallel?

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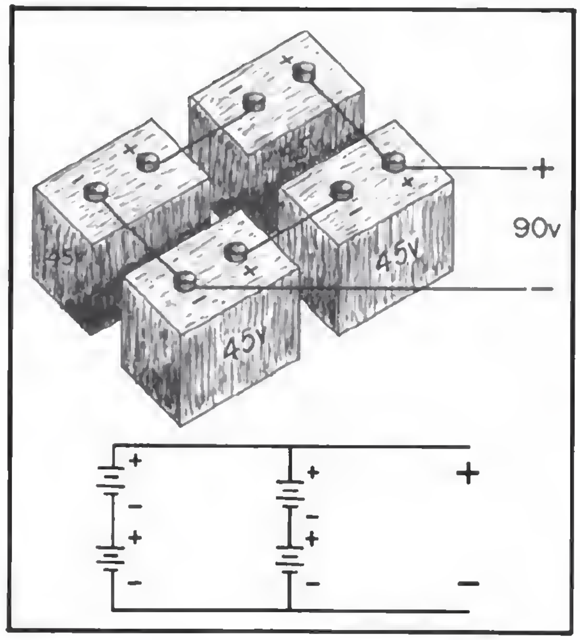

Figure 4-21 - Cells connected in series-parallel.

Q21. What is the output voltage of a battery consisting of five cells of 1.5 volts each connected in series?

4-25. Hydrometer

The specific gravity of an electrolyte is measured with a hydrometer. In the syringe-type hydrometer (Figure 4-22), part of the battery electrolyte is drawn up into a glass cylinder by means of a rubber bulb at the top.

The hydrometer float consists of a small hollow glass tube weighted at one end and sealed at both ends. A scale calibrated in specific gravity is laid off axially along the body (stem) of the float. The hydrometer float is inside the glass cylinder and the electrolyte to be tested is drawn up into the cylinder, thus immersing the hydrometer float in the solution. When the syringe is held approximately in a vertical position, the hydrometer float will sink to a certain level in the electrolyte. The extent to which the hydrometer stem protrudes above the level of the liquid depends upon the specific gravity of the solution. The reading on the stem at the surface of the liquid is the specific gravity of the electrolyte in the syringe.

A19. Positive.

A20. 1.5 volts.

A21. 7.5 volts.

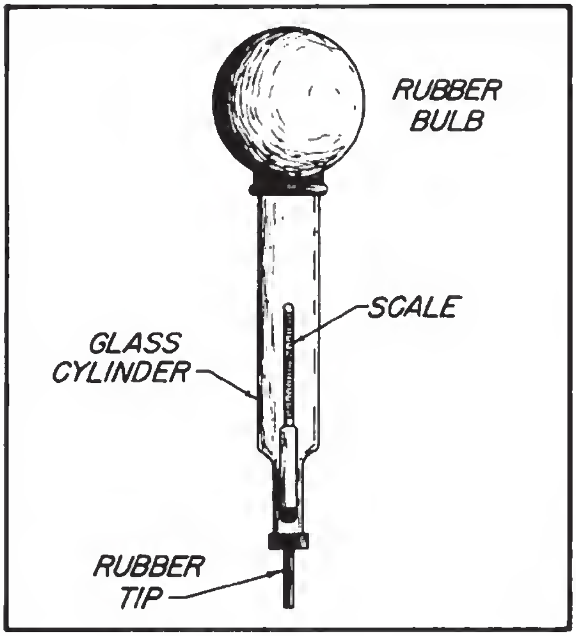

Figure 4-22 - Hydrometer.

4-26. Mixing Electrolytes.

The electrolyte of a fully charged battery usually contains about 38 percent sulfuric acid by weight, or about 27 percent by volume. In preparing the electrolyte, distilled water and sulfuric acid that meets Navy specifications is used. New batteries may be delivered with containers of concentrated sulfuric acid of 1.830 specific gravity or electrolyte of 1.400 specific gravity, both of which must be diluted with distilled water to make electrolyte of the proper specific gravity. The container used for diluting the acid should be made of glass, earthenware, rubber, or lead.

When mixing electrolyte, ALWAYS POUR ACID INTO WATER, NEVER POUR WATER INTO ACID. Pour the acid slowly and cautiously to prevent excessive heating and splashing. Stir the solution continuously with a nonmetallic rod to combine the heavier acid with the lighter water and to keep the acid from sinking to the bottom. When concentrated acid is diluted, the solution becomes very hot.

4-27. Treatment of Acid Burns

If acid or electrolyte from a lead-acid battery comes into contact with the skin or eyes, the affected area should be washed as soon as possible with large quantities of fresh water. A salve such as vaseline, boric acid, or zinc ointment should then be applied. If none of these salves are available, clean lubricating oil will suffice as an expedient. When washing, large amounts of water should be used since a small amount of water might do more harm than good in spreading the acid burn.

Acid spilled on clothing may be neutralized with dilute ammonia or a solution of baking soda and water.

4-28. DC Voltage Measurement

The function of a VOLTMETER is to measure the EMF of a voltage source or to indicate the potential difference between two points in a circuit.

In order to measure the voltage produced by a source, or dropped across a load device, the VOLTAGE-MEASURING INSTRUMENT IS CONNECTED ACROSS (IN PARALLEL WITH) THE DEVICE. If the approximate value of the potential to be measured is not known, it is best to start with the highest range of the voltmeter and progressively lower the range until a suitable reading is obtained. Caution should be used to insure that the highest range of the particular instrument is adequate before connecting the meter to the potential.

In many cases, the voltmeter is not a central zero indicating instrument. Thus, it is necessary to observe the proper polarity when connecting the instrument. The positive terminal of the voltmeter is always connected to the positive terminal of the source, and the negative terminal to the negative terminal of the source. In any case, the voltmeter is connected so that electrons will flow into the negative terminal

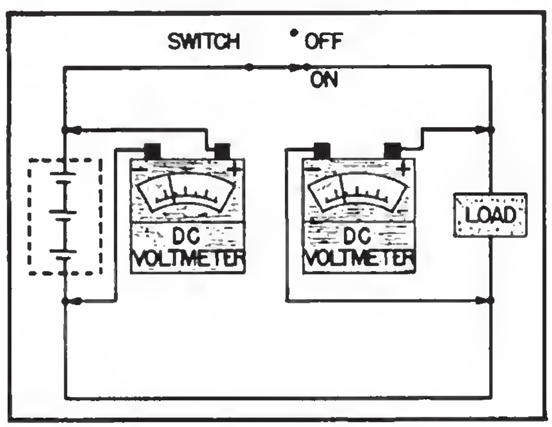

Figure 4-23 - Voltage measurement.

and out of the positive terminal of the meter. A schematic representation of the proper method for voltage measurement is shown in Figure 4-23.

EXERCISE 4

1. Define work.
2. Define energy.
3. Define potential energy.
4. Define kinetic energy.
5. What unit is used for the measurement of work?
6. Define electrical potential.
7. What unit is used for the measurement of electrical potential?
8. What is the meaning of "potential difference"?
9. What is electromotive force?
10. How many joules of work must be done on 3 coulombs of charge to develop a potential of 120 volts?
11. Describe the piezoelectric effect.
12. What type of crystals exhibit the piezoelectric effect?
13. Describe the thermoelectric effect.
14. What is a thermocouple?
15. What would be a typical output voltage for a thermocouple?
16. Describe the photoelectric effect.
17. Describe the construction of a photocell.
18. What determines the magnitude of the voltage generated by a photocell?
19. What is an induced voltage?
20. What causes the free electrons within a conductor to be displaced as the conductor is moved through a magnetic field?
21. What factors determine the magnitude of voltage induced in a conductor?
22. What is a cell?
23. What is a battery?
24. What is a primary cell?
25. What is a secondary cell?
26. Describe local action.
27. What is amalgamation as applied to cells?
28. Describe polarization.
29. How is polarization reduced in a practical cell?
30. Why is it not practical to recharge a primary cell?
31. Even though a lead-acid cell can be recharged it eventually wears out. How can this be explained?
32. What happens to the electrolyte of a lead-acid cell as the cell is discharged?
33. How can the state of charge of a lead-acid cell be determined?
34. How should a group of cells be connected to obtain the maximum possible voltage?
35. How should a group of cells be connected to obtain the maximum current delivering capabilities?

CHAPTER 5

CURRENT AND RESISTANCE

All electric and electronic devices utilize electron movement (current) and the opposition to the movement of electrons (resistance). Thus, current flow and resistance are electrical properties that warrant a thorough investigation. To adequately study this chapter, a knowledge of atomic structure, as presented in Chapter one, is required.

ELECTRIC CURRENT

In the early years of electrical study, electric current was erroneously assumed to be a movement of positive charges from positive to negative. This assumption, termed CONVENTIONAL CURRENT FLOW, is a concept that became entrenched in the minds of many scientists. Consequently, conventional current flow is found in many textbooks and its existence should be realized.

Since it has been proven that electrons (negative charges) move through a wire, ELECTRON CURRENT will be used throughout the explanation of electric current in this chapter and throughout the remainder of the text. Electron current is defined as the directed flow of electrons. The direction of electron movement, as determined in Chapter 2 is from a region of negative potential to a region of less negative potential or more positive potential. Therefore, electric current can be said to flow from a negative potential to a positive potential. The direction is determined by the polarity of the voltage source.

Electric current is generally classified into two general types—direct current and alternating current. A direct current flows continuously in the same direction whereas an alternating current periodically reverses direction. To gain a thorough understanding of the concept of current flow, it is desirable to discuss electron drift, and distinguish between random and directed drift.

5-1. Random Drift

All materials are composed of atoms, each of which is capable of becoming ionized. If a form of energy such as a phonon of heat is applied to a material, many electrons acquire sufficient energy to move to a higher energy level. As a result, many electrons are freed from their parent atoms. Other forms of energy, particularly light or an electric field, would likewise cause ionization to occur.

The number of free electrons resulting from ionization is dependent upon the quanity of energy applied to a material as well as the material's atomic structure. At room temperature some materials, classified as conductors, have an abundance of free electrons. Under a similar condition, materials classified as insulators have relatively few free electrons.

In a study of electric current, conductors are of major concern. Conductors are made up of atoms that contain loosely bound electrons in their outer orbit. Due to the effects of increased energy, these outermost electrons frequently break away from their atoms and freely drift throughout the material. The free electrons, also called mobile electrons, take a path that is not predictable and drift about the material in a haphazard manner. Consequently, such a movement is termed RANDOM DRIFT.

Due to random drift of electrons, there are a number of collisions between electrons and atoms. Each collision causes an exchange of energy to occur. As a result some ions are constantly formed while others go through the process of recombination. During recombination, an ion obtains an electron from the many that are available and causes a particle of energy to be emitted. This emitted particle may be of sufficient energy to cause, by collision, the ionization of a neighboring atom, thereby generating a new free electron. Ionization and its effects are thus transmitted throughout a material. This results in the same number of electrons per unit volume throughout the material (provided temperature, etc. are held constant).

It is important to emphasize that the random drift of electrons occurs in all materials provided the temperature is above absolute zero (-273.16° centigrade).

Q1. Compare the random drift action in a conductor to that of an insulator.

A1. The degree of random drift is greater in a conductor than that of an insulator.

5-2. Directed Drift

Associated with every charged body there is an electrostatic field. It was found that bodies that are charged alike have the ability to repel one another and that bodies with unlike charges attract each other. The force of attraction or repulsion was found to be directly proportional to the product of their charges and inversely proportional to the square of the distance separating them. This statement is an expression of Coulomb's law of charged bodies and is of great use in the consideration of the effects upon random drift when a difference in charge is impressed across a conductor. As is now known, the term DIFFERENCE IN CHARGE may be replaced with the term DIFFERENCE IN POTENTIAL.

An electron has a negative charge equal in magnitude to approximately 1.602×10^{-19} coulomb. The electron will be affected by an electrostatic field in exactly the same manner as any negatively charged body. It is repelled by a negative charge and is attracted by a positive charge. If a conductor has a difference in potential impressed across it as shown in Figure 5-1, a direction is imparted to the random drift causing the mobile electrons to be repelled away from the negative terminal and attracted toward the positive terminal. This constitutes a general migration of electrons from one end of the conductor to the other. The directed migration of mobile electrons due to the potential difference is called DIRECTED DRIFT. It may seem that the electrons now have the ability to move in a straight line from one end of the conductor to the other. However, their motion is far from being straight. In fact, it is unlikely that any electrons travel straight for an appreciable distance. As previously discussed, there is the constant collision of electrons and atoms. Upon collision the direction of the electron changes. Therefore, though the drift is directed, the electrons move in a zig zag pattern as shown in Figure 5-2.

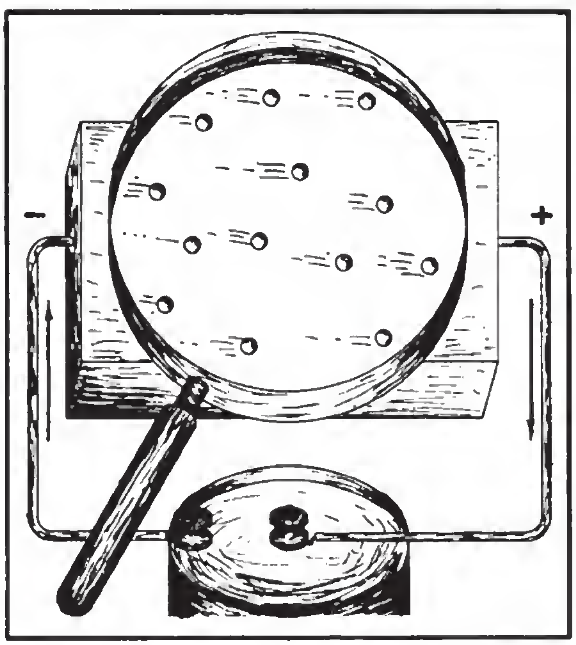

Figure 5-1 - Directed drift.

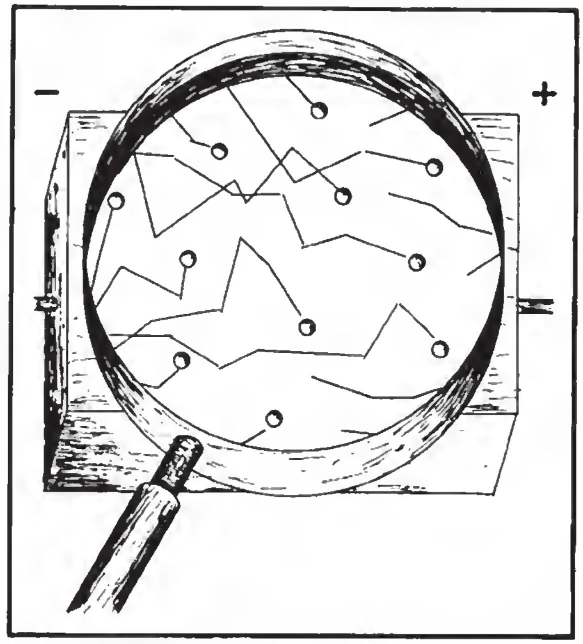

Figure 5-2 - Zig Zag migration of electrons.

The average distance between collisions is called the MEAN FREE PATH of the mobile electron. Throughout a material, the free path of electrons will differ, however, if a large number of these distances are considered and an average determined, the mean free path is established. Materials that are good conductors have relatively long mean free paths.

The directed movement of the electrons occurs at a relatively low VELOCITY (rate of motion in a particular direction). The effect of this directed movement, however, is felt almost instantaneously as explained by the use of Figure 5-3. As a difference in potential is impressed across the conductor, the positive terminal of the battery attracts electrons from point A. Point A now has a deficiency of electrons. As a result, electrons are attracted

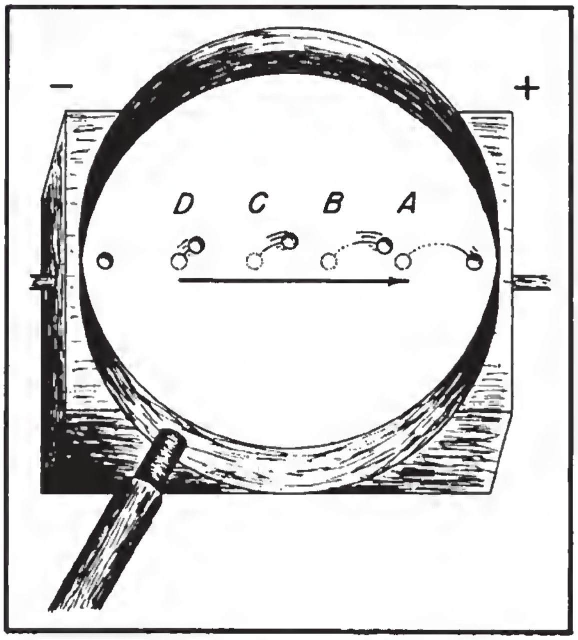

Figure 5-3 - Effect of directed drift.

from point B to point A. Point B has now developed an electron deficiency, therefore, it will attract electrons. This same effect occurs throughout the conductor and repeats itself from points C to D. At the same instant the positive battery terminal attracted electrons from point A, the negative terminal repelled electrons toward point D. These electrons are attracted to point D as it gives up electrons to point C. This process is continuous for as long as a difference of potential exists across the conductor. Though an individual electron moves quite slowly through the conductor, the effect of directed drift occurs almost instantaneously. As an electron moves into the conductor at point D, an electron is leaving at point A. This action takes place at approximately the speed of light.

Energy and its exchange is mentioned frequently and it has been discussed in different forms. For random drift to become directed drift, there is a conversion of potential energy into kinetic energy. When an electric potential is impressed across a conductor, the potential energy stored in the electric field is transferred to the free electrons. This potential energy is converted to kinetic energy, as a result of the electron's directed motion.

The potential energy of the battery is expended while being converted to kinetic energy. The kinetic energy will be released in the form of heat. Thus, as repeatedly stated, energy is neither created nor destroyed, merely converted from one form to another.

Q2. The potential energy transferred to an electron is decreased, what is the effect on the electron's kinetic energy?

5-3. Magnitude of Current Flow

Electric current has been defined as the directed movement of electrons. Directed drift therefore, is current and the terms can be used interchangeably. The expression directed drift is particularly helpful in differentiating between the random and directed motion of electrons. However, CURRENT FLOW is the terminology most commonly used in indicating a directed movement of electrons.

The magnitude of current flow is directly related to the amount of energy that passes through a conductor as a result of the drift action. An increase in the number of energy carriers (the mobile electrons) or an increase in the energy of the existing mobile electrons would provide an increase in current flow. When an electric potential is impressed across a conductor, there is an increase in the velocity of the mobile electrons causing an increase in the energy of the carriers. There is also the generation of an increased number of electrons providing added carriers of energy. The additional number of free electrons is relatively small, hence the magnitude of current flow is primarily dependent on the velocity of the existing mobile electrons.

The magnitude of current flow is affected by the difference of potential and the condition of the crystal lattice. Current flow is affected by the difference of potential in the following manner: Initially, mobile electrons are given additional energy because of the repelling and attracting electrostatic field. These electrons in turn collide with atoms releasing this energy to the atom. The electron that strikes the atom may deliver all or part of its energy to the atom. Assuming it delivers only part of its energy as indicated in Figure 5-4, the electron will continue to travel under the influence of the electric field. If the potential difference is increased, the electric field will be stronger, the amount of energy imparted to a mobile electron will be greater, and the current will be increased. If the potential difference is decreased, the strength of the field is reduced, the energy supplied to the electron is diminished, and the current is decreased.

Some crystal structures will allow electrons to pass through them with a minimum of collisions while others will present a large number of obstacles to the electron's movement. It is impossible to state a definite relationship between the crystal lattice and current for the

A2. Kinetic energy is decreased.

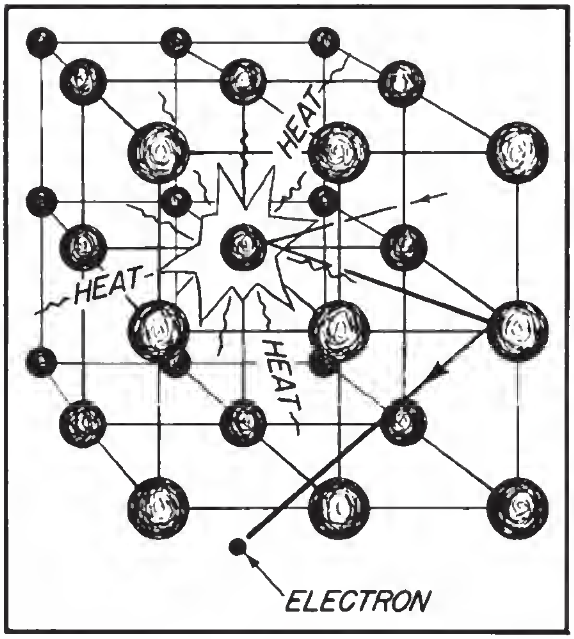

Figure 5-4 - Electron movement through crystal lattice.

configuration of the crystal will have different effects in different types of materials. However, it is safe to mention that as the obstacles to electron movement are increased, there is a decrease in current flow.

Q3. The voltage impressed across a conductor is increased from 5 volts to 10 volts, what is the effect upon current flow?

5-4. Measurement of Current

The magnitude of current is measured in AMPERES. A current of one ampere is said to flow when one coulomb of charge passes a point in one second. Expressed as an equation:

$$I = \frac{Q}{T} \qquad (5\text{-}1)$$

where: I = current in amperes

Q = charge in coulombs

T = time in seconds

Example. Four coulombs of charge drift past a point in two seconds. How much current is flowing?

I = ?

Q = 4 coulombs

T = 2 seconds

Solution:

$$I = \frac{Q}{T} \qquad (5\text{-}1)$$

$$I = \frac{4 \text{ coulombs}}{2 \text{ seconds}}$$

$$I = 2 \text{ amperes}$$

Frequently, the ampere is much too large a unit. Therefore the MILLIAMPERE (ma), one thousandth of an ampere, or the MICRO-AMPERE (ua)—one millionth of an ampere are used. The device used to measure current is called an AMMETER and will be discussed in detail later in the chapter.

Example. Two coulombs of charge flow past a point in a conductor in 10 minutes. What is the current flow?

Given: I = ?

Q = 2 coulombs

T = 10 minutes

Solution:

$$I = \frac{Q}{T} \qquad (5\text{-}1)$$

10 minutes = 600 seconds

$$I = \frac{2 \text{ coulombs}}{600 \text{ seconds}}$$

$$I = 0.00333 \text{ or } 3.33 \text{ ma}$$

Q4. The current passing through a conductor decreases from 1 ampere to 1 milliamp. How could this be accounted for?

ELECTRICAL RESISTANCE

It is known that the directed movement of electrons constitutes a current flow. It is also known that the electrons do not move freely through a conductor's crystalline structure. Some materials offer little opposition to current flow while others greatly oppose current flow. This opposition to current flow is known as RESISTANCE and the unit of measure is the OHM. The standard of measure for one ohm is the resistance provided at zero degrees centigrade by a column of mercury having a cross-sectional

area of one square millimeter and a length of 106.3 centimeters. A conductor has one ohm of resistance when an applied potential of one volt produces a current of one ampere. The symbol used to represent the ohm is the Greek letter omega(Ω).

Resistance, although an electrical property, is determined by the physical structure of a material. The resistance of a material is governed by many of the same factors that control current flow. Therefore, in the subsequent discussion, the factors that affect current flow will be used to assist in the explanation of the factors affecting resistance.

5-5. Factors Affecting Resistance

The magnitude of resistance is determined in part by the "number of mobile electrons" available within the material. Since a decrease in the number of mobile electrons will decrease current flow, it can be said that the opposition to current flow (resistance) is greater in a material with fewer free electrons. Thus, the resistance of a material is determined by the number of free electrons available in a material.

Resistance is also dependent upon the length of the "mean free path" of the electrons. As the mean free path of an electron is shortened, the current flow decreases and the resistance increases. Likewise as the mean free path of an electron is lengthened, current flow increases and resistance decreases.

Among the factors that affect the length of the electron's mean free path, other than its basic lattice structure, are the degree of lattice vibration and the presence of impurity atoms. An increase in the magnitude of the lattice vibrations throughout a material presents additional obstacles to the mobile electrons. The electron's mean free path is shortened, causing an increase in resistance. Impurity atoms are introduced into some materials during manufacture. The crystal configuration that results can either increase or decrease resistance. In the case of an increase, the mean free path is shortened. In the case of a decrease, the mean free path is lengthened. The condition which occurs is dependent upon the type of impurity present and its compatibility with the existing crystal structure.

Q5. Compare the mean free path of an electron in a conductor to an insulator.

A knowledge of the conditions that limit current flow and therefore affect resistance can now be used to consider how the type of material, physical dimensions, and temperature, will affect the resistance of a conductor.

FACTORS AFFECTING RESISTANCE OF A CONDUCTOR

5-6. Type of Material

Dependent upon their atomic structure, different materials will have different quantities of free electrons. Therefore the various conductors used in electronic applications have different values of resistance.

Consider a simple metallic substance. Most metals are crystalline in structure and consist of atoms that are tightly bound in the lattice network. The atoms of such elements are so close together that the electrons in the outer shell of the atom are associated with one atom as much as with its neighbor. (See Figure 5-5a.) As a result the force of attachment of an outer electron with any individual atom is practically zero. Depending on the metal, at least one, sometimes two, and, in a few cases, three electrons per atom exist in this state. In such a case, a relatively small amount of additional electron energy would free the outer electrons from the attraction of the nucleus. At normal room temperature materials of this type have many free electrons and are good conductors. Good conductors will have a low resistance.

If the atoms of a material are further apart, as illustrated in Figure 5-5b, the electrons in the outer shells will not be equally attached to several atoms as they orbit the nucleus. They will be attracted by the nucleus of the parent atom only, therefore a greater amount of energy is required to free any of these electrons. Ma-

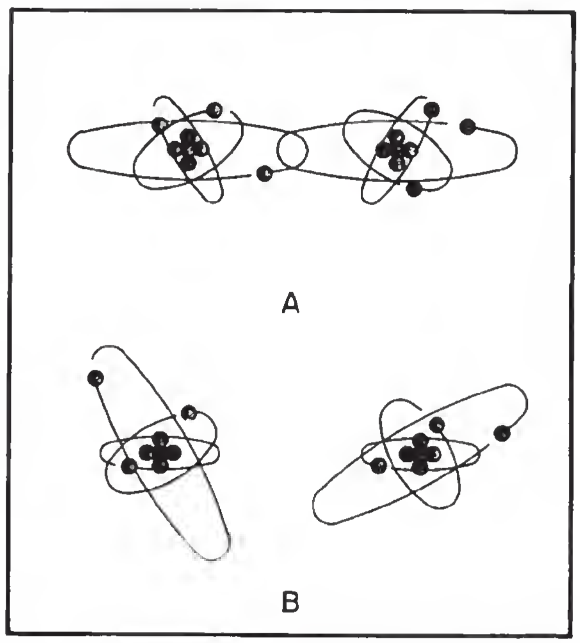

Figure 5-5 - Atomic spacing in conductors.

A3. Current flow is increased.

A4. The applied voltage has been decreased.

A5. The mean free path is greater in a conductor.

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terials of this type are poor conductors and therefore have a high resistance.

The elements silver, gold, and aluminum are examples of good conductors. Therefore, materials composed of their atoms would also have a low resistance.

The element copper is the conductor most widely used throughout electrical applications. Silver has a lower resistance than copper but its cost limits usage only to circuits where a high conductivity is demanded.

Occasionally aluminum is used for conductors where the weight of the conductor is of considerable importance.

5-7. Effect of Cross-Sectional Area

Cross-sectional area greatly affects the magnitude of resistance. If the cross-sectional area of a conductor is increased, a greater quantity of electrons are available for movement through the conductor. Therefore, a larger current will flow for a given amount of applied voltage. An increase in current indicates that when the cross-sectional area of a conductor is increased the resistance must have decreased. If the cross-sectional area of a conductor is decreased, the number of available electrons decreases and for a given applied voltage, the current through the conductor decreases. A decrease in current flow indicates that when the cross-sectional area of a conductor is decreased, the resistance must have increased. Thus, the RESISTANCE OF A CONDUCTOR IS INVERSELY PROPORTIONAL TO ITS CROSS-SECTIONAL AREA.

The diameter of conductors used in electronics is often only a fraction of an inch, therefore, the diameter is expressed in mils (1/1000 of an inch). It is also standard practice to assign the unit circular mil to the cross-sectional area of the conductor. The circular mil is found by simply squaring the diameter, when the diameter is expressed in mils. Thus if the diameter is 35 mils (0.035 inches), the circular mil area is equal to $(35)^2$ or 1,225 cir. mils. A comparison between a square mil and a circular mil is illustrated in Figure 5-6.

Q6. The diameter of one wire is double that of a second wire. Compare the relationship between the resistance of the wires.

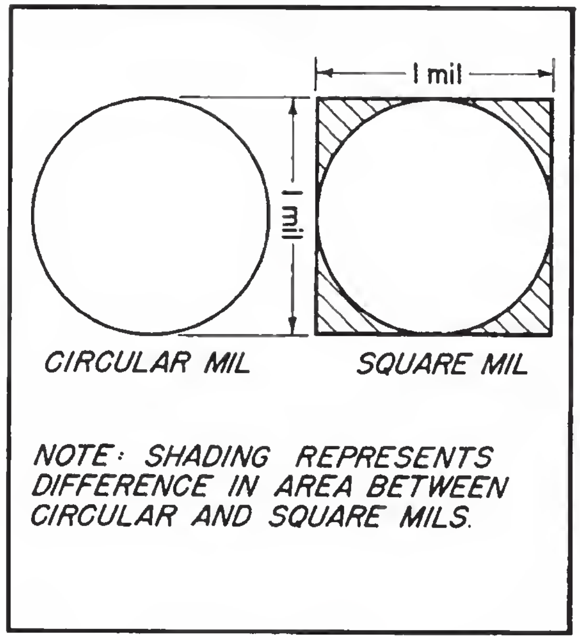

Figure 5-6 - Square and circular mil.

5-8. Effect of Conductor Length

The length of the conductor is also a factor which determines the resistance of a conductor. If the length of a conductor is increased, the number of electron collisions that occur throughout the conductor increases proportionally. As a result of the greater number of collisions, more energy is given up in the form of heat. This additional energy loss subtracts from the energy being transferred through the conductor resulting in a decrease in current flow for a given applied voltage. A decrease in current flow indicates an increase in resistance provided the voltage is held constant. Therefore, if the length of a conductor is increased, the resistance is increased. In similar fashion, if the length of a conductor is decreased, the resistance is decreased. The RESISTANCE OF A CONDUCTOR IS DIRECTLY PROPORTIONAL TO ITS LENGTH.

Q7. The length of a conductor is cut in half. What is the effect on its resistance?

5-9. Effect of Temperature

Temperature changes affect the resistance of materials in different ways. In some materials an increase in temperature causes an increase in resistance, whereas in others, an increase in temperature causes a decrease in resistance. The amount of change of resistance per unit change in temperature is known as the temperature coefficient. If for an increase in tempera-

ture the resistance of a material increases it is said to have a POSITIVE TEMPERATURE COEFFICIENT. In such materials an increase in temperature causes additional quivering of the lattice structure and thereby reduces the mean free path of the electrons. This effect tends to increase resistance. In other materials the same increase in temperature likewise causes additional lattice quivering. However, the increased number of free electrons resulting from ionization, offsets the reduction of the electron mean free path. Consequently, there is a decrease in resistance. A material whose resistance decreases with an increase in temperature has a NEGATIVE TEMPERATURE COEFFICIENT. Most conductors used in electronic applications have a positive temperature coefficient. However, carbon, a frequently used material, is a substance having a negative temperature coefficient. Several materials such as the alloys constantan and manganin are considered to have a ZERO TEMPERATURE COEFFICIENT because their resistance remains relatively constant for changes in temperature.

Q8. It is desired to construct a very sensitive measuring device. Would it be desirable to manufacture the instrument's measuring mechanism from a material having a positive temperature coefficient. Explain.

5-10. Specific Resistance

Specific resistance is a standard that has been developed to compare the resistance value of conductors. Specific resistance or resistivity is the resistance in ohms offered by the unit volume (cir-mil-foot) of a substance. In the English system, the unit volume of a material is the volume of a cylindrical conductor which is one foot long and one mil in diameter. This is illustrated in Figure 5-7. Each different conducting material has its own specific resistance, determined by the factors discussed in paragraph 5-5. Table 5-1 lists the comparative specific resistance of some common materials. Of the materials shown, silver has the least resistance and is the best conductor.

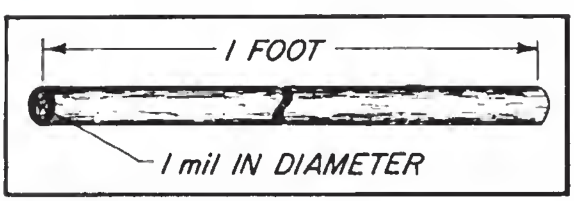

Figure 5-7 - The circular-mil-foot

	Specific resistance at 20°C	
Substance	Centimeter cube (microhms)	Circular mil-foot (ohms)
Silver	1.629	9.8
Copper (drawn)	1.724	10.37
Gold	2.44	14.7
Aluminum	2.828	17.02
Carbon (amorphous.)	3.8 to 4.1	. . . .
Tungsten	5.51	33.2
Brass	7.0	42.1
Steel (soft)	15.9	95.8
Nichrome	109.0	660.0

Table 5-1 - Specific Resistance

The resistance of a conductor of uniform diameter is equal to the product of its length and specific resistance, divided by its cross-sectional area. Expressed as an equation:

$$R = \rho\frac{L}{A} \qquad (5\text{-}2)$$

where: R = resistance in ohms

(Greek rho)ρ = specific resistance (ohms/cir-mil-foot)

L = length in feet

A = area in cir mils

Example. What is the resistance of 500 ft. of copper wire having a diameter of 0.002 inches?

Given: $L = 500$ ft.

$D = 0.002$ inches

From Table: $\rho = 10.37$

Solution: $R = \rho\frac{L}{A}$

0.002 inches = 2 mils

$A = D^2$

$A = (2)^2$

$A = 4$ circular mils

$R = \rho\frac{L}{A}$

$R = 10.37 \times \frac{500}{4}$

$R = 1,293$ ohms

A6. The resistance of the first wire is one fourth that of the second.

A7. The resistance is halved.

A8. No. Such a material's resistance changes with temperature.

Q9. The area of a conductor is doubled, how is the specific resistance affected?

5-11. Conductance

Electronics is a study that is frequently explained in terms of opposites. The term that is just the opposite of resistance is conductance. Conductance is the ability of a material to pass electrons. The factors that effect the magnitude of resistance are exactly the same for conductance, but they affect conductance in the opposite manner. Therefore, conductance is directly proportional to area, and inversely proportional to the length and specific resistance of the material. The temperature of the material is definitely a factor, but assuming a constant temperature, the conductance of a material can be calculated if its specific resistance is known.

The formula for conductance is:

$$G = \frac{A}{pL} \qquad (5\text{-}3)$$

where: G = conductance measured in mhos

A = cross-sectional area in cir mils

L = length measured in feet

p = specific resistance

The unit of conductance is the MHO, which is ohm spelled backwards. Whereas the symbol used to represent the magnitude of resistance is the Greek letter omega (Ω), the symbol used to represent conductance is $\mho$. The relationship that exists between resistance and conductance is a reciprocal one. A reciprocal of a number is one divided by that number. In terms of resistance and conductance:

$$R = \frac{1}{G} \qquad (5\text{-}4)$$

$$G = \frac{1}{R} \qquad (5\text{-}5)$$

If the resistance of a material is known, dividing its value into one will give its conductance. Also, if the conductance is known, dividing its value into one will give its resistance. From the example problem in section 5-10, the resistance was found to be 1,296 ohms. The equivalent conductance will be:

$$G = \frac{1}{R} = \frac{1}{1,296} = 0.000772 \text{ mhos}$$

The value for the conductance is seen to be very small. Since the possibility of error is great when working with numbers of such minute magnitude, the value can be expressed in micromhos. Therefore, the conductance of 0.000772 mhos is 772 micromhos.

5-12. Wire Gauge

Various electrical applications demand different conductor sizes. Some wires are extremely large, and others are almost as fine as human hair. All wire is designated by definite gauge sizes. Each number designates a wire of specific diameter. As the diameter of the wire decreases, the gauge number increases. The following table illustrates some various wire sizes, their comparative areas and resistance per 1000 ft. The resistance values apply only to copper conductors.

Gauge Number	Diameter (mils)	Cross Section Circular (mils)	Ohms per 1000 ft. 25°C. (=77°F.)
0000	460.0	212,000.0	.0500
2	258.0	66,400.0	.159
6	162.0	26,300.0	.403
10	102.0	10,400.0	1.02
14	64.0	4,110.0	2.58
18	40.0	1,620.0	6.51
22	25.3	642.0	16.5
26	15.9	254.0	41.6
30	10.0	101.0	105.0
36	5.0	25.0	423.0
38	4.0	15.7	673.0
40	3.1	9.9	1,070.0

Table 5-2 - Standard annealed solid copper wire

ELECTRICAL RESISTORS

Resistance is a property of every electrical component. At times, its effects will be undesirable. However, resistance is used in many varied ways. RESISTORS are components manufactured to possess specific values of resistance. They are manufactured in many different

types and sizes. When drawn in a schematic, a resistor is represented by a series of jagged lines as shown in Figure 5-8.

5-13. Composition of Resistors

One of the most common types of resistors is the CARBON resistor illustrated in Figure 5-8A. This type, with the leads extending parallel to the length of the resistor, is known as an axial lead resistor. Carbon resistors, as you might suspect, have as their principal ingredient the element carbon. The specific resistance of carbon lies between the range of 20 to 27 ohms per cir-mil-ft. Carbon has a conductance that is approximately one-five hundredth that of silver. In the manufacture of carbon resistors, fillers or binders are added to the carbon to obtain various resistor values. Examples of fillers are clay, bakelite, rubber, and talc. These fillers are doping agents and cause the overall conduction characteristics to change. Carbon resistors are the most common resistors found because they are easy to manufacture, inexpensive, and have a tolerance that is adequate for most electronic applications. Their prime disadvantage is that they have a tendency to change value as they age. One other disadvantage of carbon resistors is their limited power handling capacity.

The disadvantages of carbon resistors can be overcome by the use of WIRE WOUND resistors (Figure 5-8B). Wire wound resistors have very accurate values and possess a higher current handling capacity than carbon resistors. The material that is frequently used to manufacture wire wound resistors is German silver which is composed of copper, nickel, and zinc. The quantities of these elements present determine the resistivity, but the resistivity will be primarily dependent on the percentage of nickel present. One disadvantage of wire wound resistors is that it takes a large amount of wire to manufacture a resistor of high ohmic value, thereby increasing cost.

Q10. It is desired to construct a wire wound resistor of 100 ohms. If 20 ft. of wire is wound on an insulator to construct a 25 ohm resistor, how can a 100 ohm resistor be constructed using the same type of wire?

5-14. Fixed and Variable Resistors

There are two kinds of resistors. FIXED and VARIABLE. The fixed resistor will have one value and will not be subject to change other than temperature, age, etc. The resistors indicated in Figure 5-8 and 5-9 are all classed as fixed resistors. The tapped resistor, illustrated in Figure 5-9A has several fixed taps and furnishes more than one resistance value. The sliding contact resistor, indicated in Figure 5-9B, has an adjustable collar that can be moved to tap off any resistance value within the range of the resistor. Such a resistor does not completely fulfill the requirements of a fixed resistor. However, the collar is normally adjusted to a desired position and kept there. The

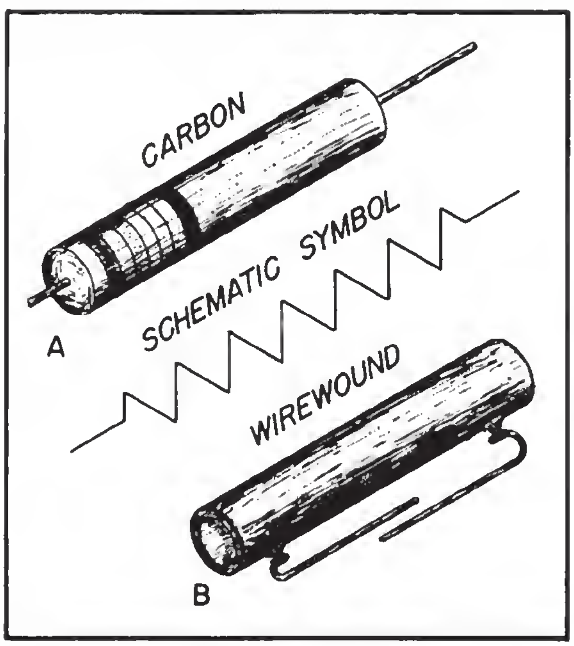

Figure 5-8 - Carbon and wire wound resistors.

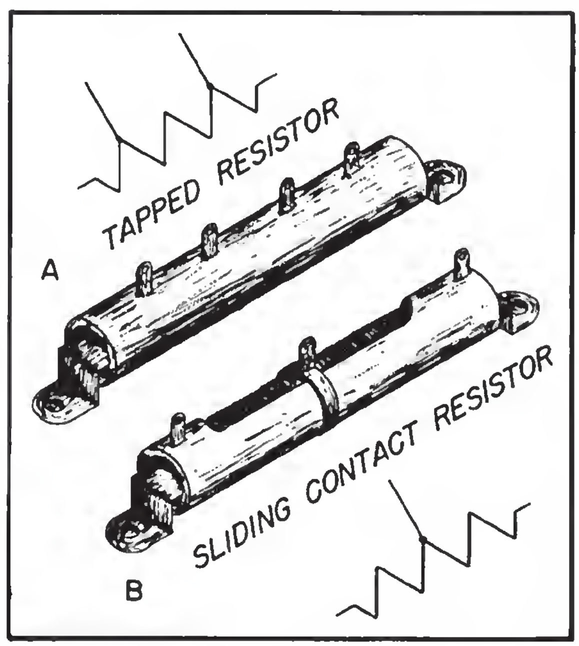

Figure 5-9. Tapped resistors.

A9. Specific resistance remains unchanged.

A10. Increase length of wire to 80 ft.

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sliding contact resistor thus serves as a fixed tapped resistor.

The variable resistor is of two types. One is called a POTENTIOMETER and the other is called a RHEOSTAT as shown in Figure 5-10. There is a slight difference between them. Rheostats have two connections, one fixed and one movable. The potentiometer has three contacts—two fixed and one variable. Generally the rheostat has a limited range of values and a high current handling capacity. The potentiometer has a wide range of values, but it has a limited current handling capacity.

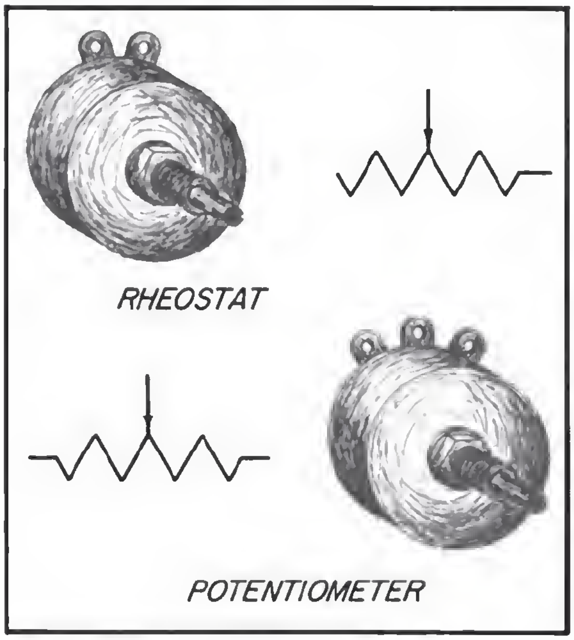

Figure 5-10 - Variable resistors.

5-15. Wattage Rating

When a current is passed through a resistor heat is developed within the resistor. The resistor must be capable of dissipating this heat into the surrounding air; otherwise the temperature of the resistor rises causing a change in resistance, or possibly causing the resistor to burn out.

The ability of a resistor to dissipate heat depends on the amount of its surface which is exposed to the air. A resistor designed to dissipate a large amount of heat must therefore have a large physical size.

The heat dissipation capability of a resistor is measured in WATTS (this unit will be explained in detail in Section 6-10). Some of the more common wattage ratings of carbon resistors are: one-eighth watt, one-fourth watt, one-half watt, one watt, and two watts. The higher the wattage rating of the resistor the larger the physical size. Resistors that require large amounts of power (watts) to be dissipated are usually wire-wound. Wire-wound resistors with wattage ratings up to 50 watts are not uncommon.

COLOR CODE

There are two systems to designate the ohmic value of resistors. One is called the standard system (most common), and the other is called the body-end-dot system. Both systems make use of a color code. The position of the color and the color code indicate the value of the resistor.

5-16. Standard System

In the standard system, four bands are painted on the resistor as shown in Figure 5-11A.

The color of the first band indicates the value of the first significant digit. The color of the second band indicates the value of the second significant digit. The third color band represents a decimal multiplier by which the first two digits must be multiplied to obtain the resistance of the resistor. The final band indicates the tolerance of the resistor. The colors used for the bands, and their corresponding values are shown in Table 5-3.

Using the example colors shown in Figure 5-11A, since red is the color of the first band, the first significant digit is (2). The second band is blue, therefore the second significant figure is (6). The third band is orange which indicates that the number formed as a result of reading the first two bands is multiplied by 1000. In this case 26 x 1000 = 26,000 ohms. The last band indicates the tolerance. Its color is silver, and the tolerance is 10 percent. The allowed limit of variation in ohmic value will be from 23,400 to 28,600 ohms.

Q11. A carbon resistor has a resistance of 50 ohms, and a tolerance of 5 percent. What are the colors of band one, two, three, and four respectively?

5-17. Body-End-Dot System

The body-end-dot method of color coding is used with radial-lead resistors. The colors correspond to the same numbers as given in

Table 5-3. The colors, position, and significance are shown in Figure 5-11B.

Color	Significant Figure	Decimal Multiplier	Resistance Tolerance Percent ±
Black	0	1	
Brown	1	10	---
Red	2	100	---
Orange	3	1,000	---
Yellow	4	10,000	---
Green	5	100,000	---
Blue	6	1,000,000	---
Violet	7	10,000,000	---
Gray	8	100,000,000	---
White	9	1,000,000,000	---
Gold	---	.1	5
Silver	---	.01	10
No Color	---		20

Table 5-3 - Standard color code for resistors.

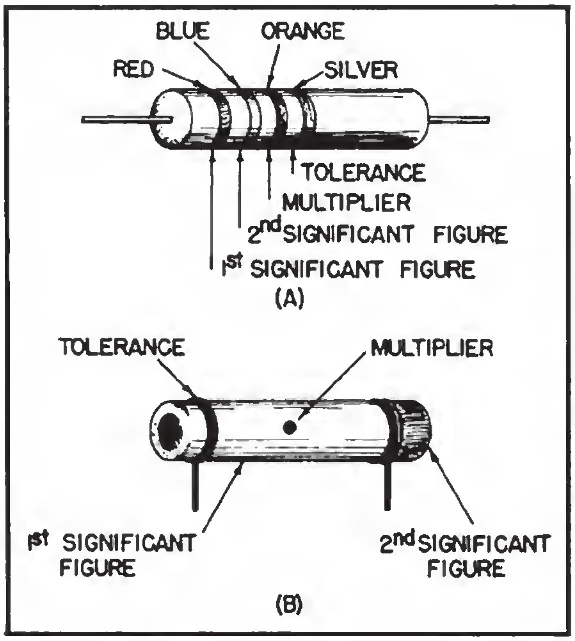

Figure 5-11 - Resistor color codes.

A. The color of the body indicates the value of the first significant figure.

B. The color of the end band to the right of the center dot gives the second significant figure.

C. The color of the dot indicates the decimal multiplier.

D. A gold or silver end indicates a tolerance of five or ten percent, respectively. If the end has no color, the tolerance is twenty percent.

Q12. Referring to question number eleven, describe the same resistor if it had been marked with the Body-End-Dot system of color coding.

METER USAGE

5-18. Ammeter

The AMMETER is a device used to measure current flow. When measuring the magnitude of current through a device, the ammeter must be inserted into the current path between the voltage source and the device. To measure direct current (dc), the ammeter is connected in such a fashion that current flow is through the meter from the negative to positive meter lead. This is illustrated in Figure 5-12. If the connections are reversed, the meter will attempt to read in the wrong direction and the meter movement will be damaged. AN AMMETER SHOULD NEVER BE CONNECTED ACROSS A RESISTOR OR OTHER DEVICE IN AN EFFORT TO MEASURE CURRENT! This would result in permanent damage to the meter. The meter must always be connected in series with the load.

The ammeter measures current flow in the basic unit of current measurement, the ampere. In many electrical and electronic applications, the magnitude of current flow is much smaller than an ampere. Consequently, in order to ac-

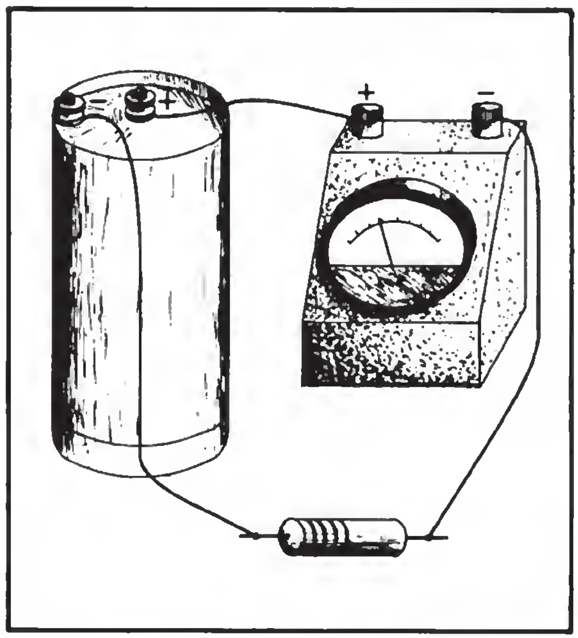

Figure 5-12 - Current measurement.

A11. The bands are green, black, black and gold.

A12. The body is green, the end is black and the dot is black.

curately measure milliamperes and microamperes of current, the milliammeter or microammeter is used.

When measuring current flow, it is important to select the proper meter. If a milliammeter or microammeter were inserted into a current path where amperes of current existed, the meter would be damaged. When the approximate magnitude of current is unknown, it is good practice to first use a meter having a high range, a meter that is capable of withstanding a large current flow. If no meter deflection is noted, further substitution of meters having progressively lower ranges is required.

5-19. Ohmmeter

An OHMMETER is a device used to measure the resistance of an electrical device. Current to operate the meter is provided by a calibrated voltage source within the meter. When measuring resistance, power to the device being tested must be shut off. The power of the device would interfere with the meter voltage source and damage the meter. NEVER CONNECT AN OHMMETER TO A LIVE CIRCUIT! The ohmmeter is connected in parallel with or directly across the component being tested. Polarity of the test leads is not important when measuring resistors (Figure 5-13).

Most ohmmeters have more than one range. When the range is changed, the meter must be recalibrated before any readings are taken. To calibrate the ohm scale connect the ends of the test leads together. The needle will deflect toward the zero ohms marking. Using the zero adjust knob, move the needle to read zero ohms.

An ohmmeter indicates resistance by measuring the amount of current it is able to force through the component under test. In certain instances it may be necessary to disconnect one end of the part under test to make sure the meter is indicating the resistance of that part alone.

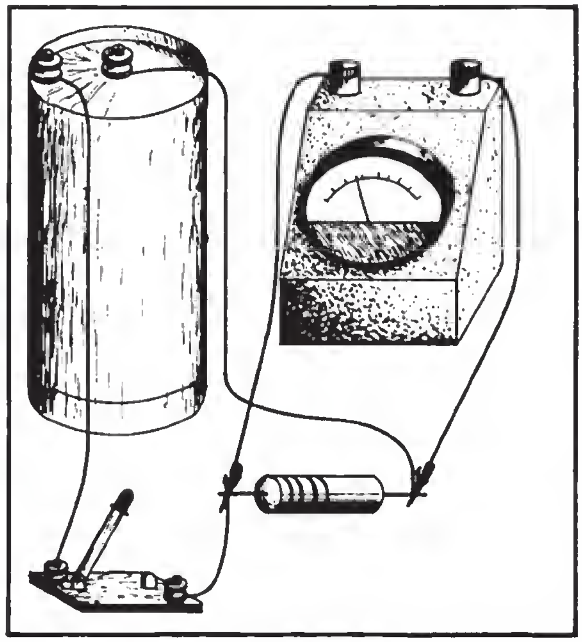

Figure 5-13 - Resistance measurement.

EXERCISE 5

1. What is a free electron?
2. Describe the effect of the collision of a high energy electron with an atom.
3. What is meant by the term random drift?
4. Give two factors that affect the magnitude of random drift.
5. How is a directed drift produced?
6. Apply Coulomb's Law to directed drift.
7. What is kinetic energy?
8. What are the factors that affect the magnitude of kinetic energy?
9. How does an electron dissipate its kinetic energy?
10. Define current and give the symbols used to represent current?
11. In what unit is current measured? How is the unit divided?
12. Give two reasons why a material provides opposition to the movement of electrons through it?
13. Define and give the unit of measure of resistance.
14. What are the factors that determine the magnitude of resistance?
15. A conductor has a diameter of 0.012 inches, what is its cir-mil area?
16. A conductor has a cir-mil area of 10, 240. What is its diameter?
17. What is the difference between a #000 wire and a #31 wire?
18. How does an increase in cross-sectional area effect resistance?
19. How does a decrease in length affect the resistance of a conductor?
20. What is the standard for specific resistance?
21. A copper conductor has a diameter of 0.064 inches and a length of 150 ft. What is its resistance?
22. A silver conductor has a length of 60 ft. and a diameter of 0.0032 inches. What is its resistance?
23. A material has a resistance of 720 ohms. Its length is 60 ft. and its diameter is 0.012 inches. What is its specific resistance?
24. The term "doping" means?
25. A material has a positive temperature coefficient. If the temperature is decreased what happens to resistance?
26. What is meant by a negative temperature coefficient?
27. What is conductance?
28. What is the relationship of conductance to resistance?
29. What are the symbols and the unit for conductance?
30. Find the conductance of the materials in problems 21 and 22.
31. Define a fixed resistor.
32. A variable resistor has two contacts. What type is it?
33. Compare the advantages and disadvantages of carbon and wire wound resistors.
34. A carbon resistor is coded white, red, blue and gold. What is its resistance?
35. A resistor is designated in the following manner. The first band is blue, the second green, the third is yellow. Give the range of values.
36. A resistor's body is green, one end is violet, the other end is gold and the dot is black. What is its range of resistance values?

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CHAPTER 6

SERIES DC CIRCUITS

In the previous two chapters, voltage, current, and resistance were thoroughly investigated. In the material that follows, these quantities will be utilized to develop the fundamental structure from which all electrical and electronic devices originate. This fundamental structure or system is called a CIRCUIT. In its simplest form a circuit consists of three basic parts which are: the SOURCE, the LOAD, and the CONDUCTORS. The source is a device, such as a battery, which supplies electrical energy to the circuit. The electrical energy is carried from the source to the load by the conductors which are usually in the form of wire. The load, which may be a device such as an electric light bulb, or an electric motor, is the receiver of electrical energy.

In order to solve the problems which normally arise in studying electric circuits of the type contained in this chapter, the reader should be familiar with the following mathematical principles: transposition of equations, graphing of equations, and extracting square roots. These subjects are presented in Volume 8.

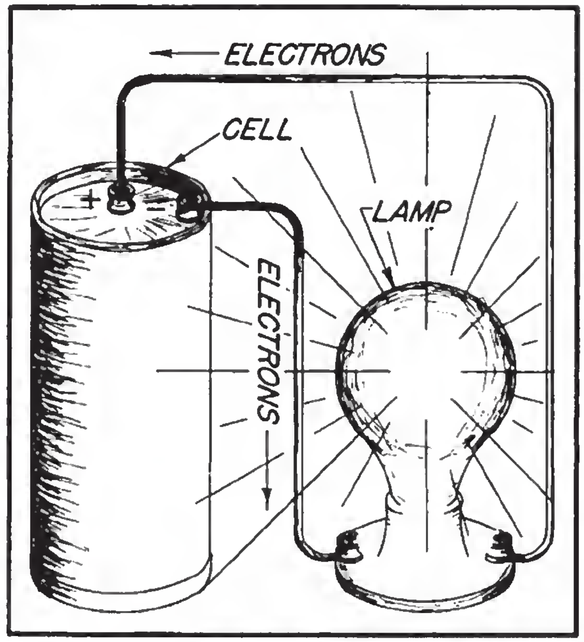


Figure 6-1 - Pictorial diagram of a basic circuit.

THE SIMPLE CIRCUIT

6-1. Operation of a Simple Circuit

A pictorial diagram of a simple electric circuit is shown in Figure 6-1. In this circuit a dry cell acts as the voltage source, a light bulb is used for a load, and the connecting wires serve to complete the conducting pathway. The light bulb may be thought of as a resistor since the internal element used to produce light is nothing more than a coil of high resistance wire.

As a result of chemical action, free electrons are piled up on the negative terminal of the dry cell and removed from the positive terminal. This action creates a difference of potential (voltage) between the terminals of the cell. This difference of potential acts upon the free electrons within the conductors to cause a directed drift or electron current.

In Figure 6-1, the electrons are forced off of the negative terminal of the source, through the external circuit (lamp and conductors), to the positive terminal of the source, where chemical action transports them back to the negative terminal on which they originated. The amount of current in the circuit is limited by the light bulb—the resistive element of the circuit. The resistance of the connecting wires is very low and is considered to be negligible in most practical applications.

It must be emphasized that in order to have current flow, there must be a complete circuit. If only one side of the light bulb were connected to a battery terminal there would not be a complete circuit. Keep in mind that when a wire is connected to one battery terminal only, there is a brief directed movement of electrons until the potential at the battery terminal is present at the free end of the wire. This directed movement of electrons is slight and cannot develop enough heat to cause illumination of the bulb. Therefore, though this momentary action fits our definition for current flow, it will not be considered as such. Current will flow only in a complete circuit.

Q1. A conductor in a simple circuit becomes opened. Describe the voltage present across the open.

6-2. Schematic Representation

A SCHEMATIC is a diagram in which symbols are used for the various components instead of pictures. These symbols are used in an effort to make the diagrams easier to draw and easier to understand. In this respect, schematic symbols aid the technician in the same way that shorthand aids the stenographer. In previous chapters the schematic symbols for cells and resistances were presented. These symbols will now be used to discuss the circuit of Figure 6-1.

In this text, any circuit which consists of a single source and a single load device (such as Figure 6-1) will be called a BASIC CIRCUIT.

A schematic diagram of the basic circuit is shown in Figure 6-2. The battery will be designated by the letter symbols E_{bb}, the light bulb in the circuit is labeled R_1. Since in reality the light bulb element is nothing more than a wire wound resistor, the conventional resistor symbol will be used for the bulb in this discussion. It should be noted, however, that the light bulb has its own specific schematic symbol and is not normally drawn as a resistor. The standard symbol used for a light bulb will be discussed at a later time when need arises.

In studies of electricity and electronics many circuits are analyzed which consist mainly of specially designed resistive components. As previously stated, these components are called resistors. Throughout the remaining analysis of the basic circuit, the resistive component will be a physical resistor. However, the resistive component could be any one of several electrical devices.

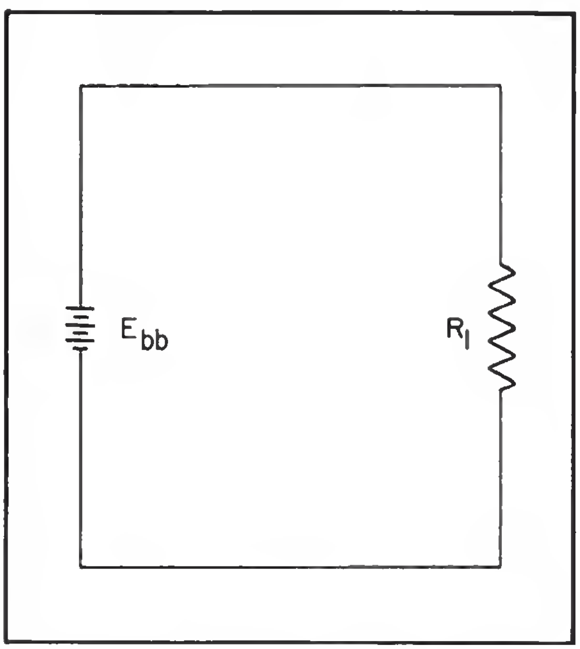


Figure 6-2 - Schematic diagram of basic circuit.

Q2. How might an electric toaster be schematically indicated?

SAFETY DEVICES

6-3. Switches

In practically all electrical equipment it is undesirable to have the circuits operate continuously. At one time or another for purposes of safety, convenience, or repair, it is necessary to remove the electrical energy from a circuit. Whenever electrical energy is applied to a circuit, the circuit is said to be ENERGIZED. When no electrical energy is applied to the circuit, the circuit is said to be DEENERGIZED.

To deenergize a circuit, the flow of current through the circuit must be stopped. In section 6-1 it was stated that in order to have current flow, a complete path must be provided from the negative terminal of the source, around through the load device, and then back to the positive terminal of the source. Thus, the easiest way to stop the flow of current (deenergize the circuit) is to disconnect or open one of the conductors interrupting the complete path.

A device called a SWITCH is used for opening and closing circuits. These switches are constructed in such a way that the person operating the switch cannot come into electrical contact with the circuit being energized or deenergized. This type of construction is used to prevent operating personnel from receiving an electrical shock which under certain circumstances could be fatal.

Switches are manufactured in hundreds of different types and current ratings. Some switches open a single conductor or circuit, while others are designed to open or close many circuits simultaneously. The various individual types of switches will be discussed as they are used. The schematic symbol for a switch used to open or close a single conductor is shown in Figure 6-3.

6-4. Electrical Fuses

When using an electrical device, care must be taken that the electric current passing through the device does not become excessive. All electrical apparatus contain a certain amount of resistance, and when electric current passes through a resistance, electric energy is

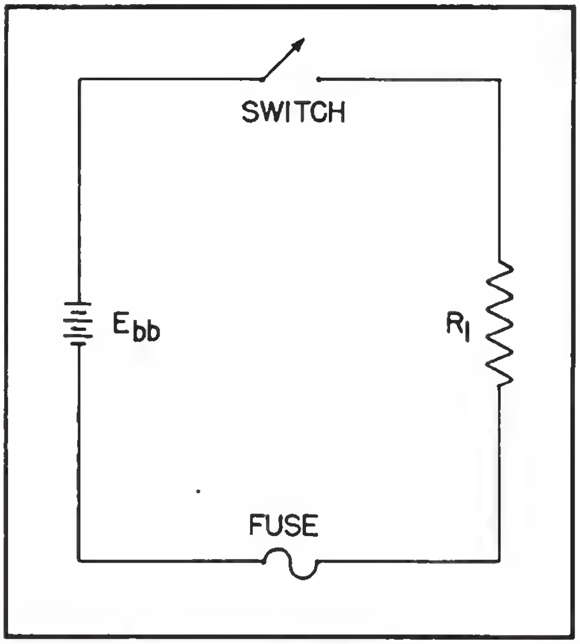


Figure 6-3 - Circuit showing the use of a fuse and switch.

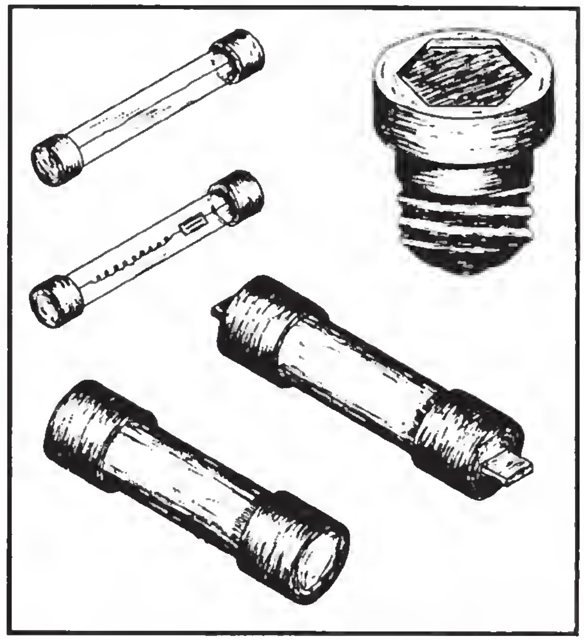


Figure 6-4 - Types of fuses.

transformed into heat energy. If faulty circuit operation causes an excess amount of current flow through an electrical device, the resulting increased temperature could cause considerable damage. For protection from such occurrences it is necessary to have an inexpensive electrical component that instantly opens the circuit when subjected to excessive current. Such a device is called a FUSE. Several types of fuses are illustrated in Figure 6-4.

Fuses are fabricated from wire made of zinc or similar metals having a low resistance value and a low melting point. When the current in a circuit is less than or equal to the current rating of the fuse, the element of the fuse is below its melting temperature. However, as soon as current flow in the circuit exceeds the current rating of the fuse, the fuse element melts rapidly due to the increased heat. Hence, the circuit will open and the circuit components are protected.

Since a fuse is placed into a circuit for reasons of safety, a blown fuse should ALWAYS be replaced with another fuse having the SAME rating as the original fuse. NEVER replace a fuse with one having a higher current rating, or use a piece of wire in place of a fuse. Though the circuit may become temporarily operational by improper replacement of a fuse, the circuit is left completely unprotected. Any sudden surge of current will not only damage circuit components, but may also set fire to the surrounding area.

The insertion of a switch, a fuse, or both into a circuit will not effectively change the operation of the circuit since these electrical devices are constructed so that they will have negligible resistance. Figure 6-3 shows the proper placement and schematic symbol for a fuse. The fuse must always be placed in series with the components to be protected.

Q3. A fuse is placed into the basic circuit to protect an electrical component. Does it matter in which part of the circuit the fuse is inserted? Explain.

Q4. Would it be safe to replace a fuse with one having a lower current rating?

RISE AND FALL OF POTENTIAL

6-5. Potential Rise

In a previous discussion on cells and batteries, it was stated that the terminal voltage developed by a cell depends on the joules of work done in moving each coulomb of charge through the electrolyte. Figure 6-5 shows an animated drawing of the action within a cell. In the drawing, chemical forces are depicted moving one coulomb of negative charge from the positive

A1. Equal to the applied voltage since each side of the open is the same as extending the battery terminals.

A2. As a resistor.

A3. No. The current stops if the circuit opens at any point.

A4. Yes. However, it might blow at the slightest overload.

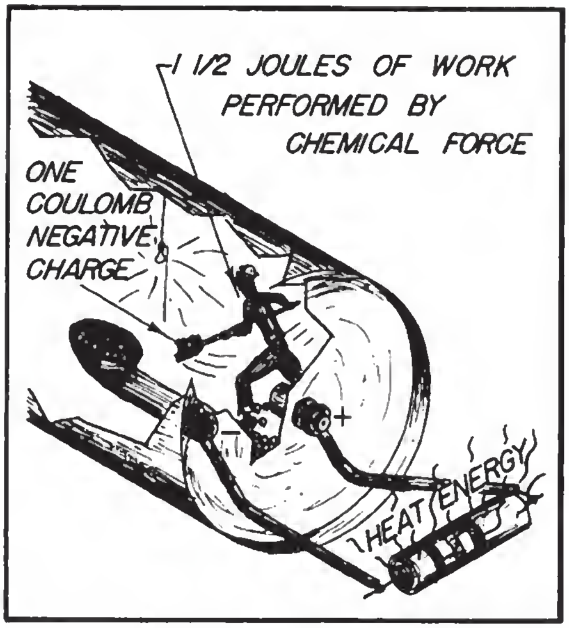


Figure 6-5 - Rise and fall of potential.

terminal (carbon rod) to the negative terminal (zinc case). In order to move one coulomb of negative charge to the negative terminal, chemical forces have to do one and one-half joules of work. Thus, the potential at the negative terminal is one and one-half joules per coulomb, or one and one-half volts greater than the potential at the positive terminal. In the language of electronics, this is spoken of as a one and one-half volt RISE IN POTENTIAL. For this case it is a one and one-half volt rise in NEGATIVE potential.

6-6. Fall of Potential

Once the electrons have reached the negative terminal of the source, they are at the highest point of negative potential in the circuit. If the electrons are now allowed to flow out of the negative terminal and through the resistor, the one and one-half joules of work stored in the electrons as potential energy can be recovered as work. As the electrons flow through the resistor, they give up their energy in the form of heat. This heat is radiated into the surrounding air by the resistor.

The farther through the resistor the electrons travel the more energy they lose. Upon reaching the end of the resistor, practically all of their original potential energy has been converted to heat energy. This loss of potential as the electrons travel through the resistor is called a FALL IN POTENTIAL or a VOLTAGE DROP. In this example the voltage drop across the resistor is one and one-half volts.

Q5. How much voltage drop would occur at a point half way through the resistor in Figure 6-5?

6-7. Important Conclusions

A close examination of the ideas developed up to this point leads to several important conclusions. Since energy cannot be created or destroyed, all of the work performed by chemical forces in producing the rise in potential across the source is recovered as heat energy developed in the resistor. Thus, THE VOLTAGE DROP ACROSS THE RESISTOR MUST EQUAL THE VOLTAGE RISE ACROSS THE SOURCE. Since voltage is equal to joules of energy per coulomb of charge, and the joules of source energy equal the joules of heat energy in the resistor, the flow of charge through the

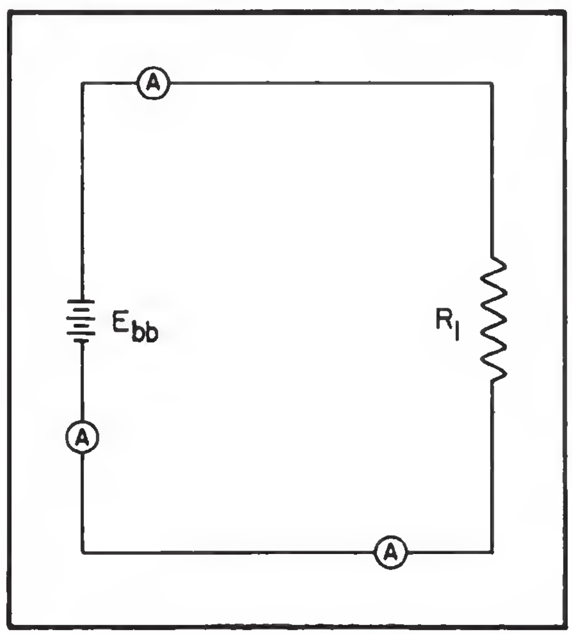


Figure 6-6 - Current measurement in basic circuit.

source must equal the flow of charge through the resistor. Thus, THE SAME CURRENT FLOWS IN EACH PART OF THE BASIC CIRCUIT.

Proof of the fact that current is the same at any point in a simple circuit is obtained by inserting several ammeters in a circuit as shown in Figure 6-6. The reading of each meter is exactly the same, thus indicating equal values of current.

RELATIONSHIP OF I, E, AND R

6-8. Ohm's Law

In the early part of the 19th century Georg Simon Ohm proved by experiment that a precise relationship exists between current, voltage, and resistance. This relationship is called Ohm's Law and is stated as follows:

LAW 1. The current in a circuit is DIRECTLY proportional to the applied voltage and INVERSELY proportional to the circuit resistance. Ohm's Law may be expressed as an equation:

$$I = \frac{E}{R} \tag{6-1}$$

where: I = current in amperes

E = voltage in volts

R = resistance in ohms

If any two of the quantities in equation (6-1) are known, the third may be easily found. For example, Figure 6-7 shows a circuit containing a resistance of 1.5 ohms and a source voltage of 1.5 volts. How much current flows in the circuit?

Given: E = 1.5 volts

R = 1.5 ohms

I = ?

Solution: $I = \frac{E}{R}$

$I = \frac{1.5}{1.5}$

I = 1 amp.

To observe the effect of source voltage on circuit current, the above problem will be solved again using double the previous source voltage.

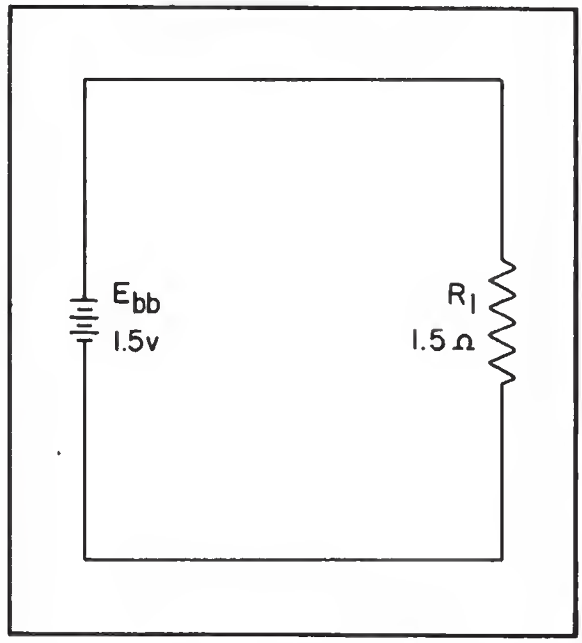


Figure 6-7 - Determining current in a basic circuit.

Given: E = 3 volts

R = 1.5 ohms

I = ?

Solution: $I = \frac{E}{R}$

$I = \frac{3}{1.5}$

I = 2 amps

Notice that as the source voltage doubles, the circuit current also doubles. Circuit current is directly proportional to applied voltage and will change by the same factor that the voltage changes.

Q6. If the source voltage in Figure 6-7 is decreased to one-half its original value, what would the new current be?

To verify the statement that current is inversely proportional to resistance, assume the resistor in Figure 6-7 to have a value of 3 ohms.

A5. One-half of the total voltage drop.

A6. 0.5 amps, one-half the original current.

Given: $E = 1.5$ volts

$R = 3$ ohms

$I = ?$

Solution:
$$I = \frac{E}{R} \qquad (6\text{-}1)$$

$$I = \frac{1.5}{3}$$

$$I = 0.5 \text{ amp}$$

Comparing this current of 0.5 amp for the 3 ohm resistor, to the 1 amp of current obtained with the 1.5 ohm resistor, shows that doubling the resistance will reduce the current to one-half the original value. Circuit current is inversely proportional to the circuit resistance.

Q7. What would be the effect on circuit current if both the source voltage and the circuit resistance were doubled?

In many circuit applications current is known and either the voltage or the resistance will be the unknown quantity. To solve a problem in which current and resistance are known, the basic formula for Ohm's Law must be transposed to solve for E as follows:

Basic equation:
$$I = \frac{E}{R} \qquad (6\text{-}1)$$

Multiply both sides of the equation by R.

$$IR = \frac{E}{\cancel{R}}\cancel{R}$$

$$IR = E$$

$$E = IR \qquad (6\text{-}2)$$

To transpose the basic formula when resistance is unknown:

Basic equation:
$$I = \frac{E}{R} \qquad (6\text{-}1)$$

Multiply both sides of the equation by R.

$$IR = \frac{E}{\cancel{R}}\cancel{R}$$

$$IR = E$$

Divide both sides of the equation by I.

$$\frac{\cancel{I}R}{\cancel{I}} = \frac{E}{I}$$

$$R = \frac{E}{I} \qquad (6\text{-}3)$$

Example: What voltage is required to properly light a lamp having a resistance of 10 ohms and a current rating of 1 ampere?

First draw a circuit like Figure 6-8 including all the given information.

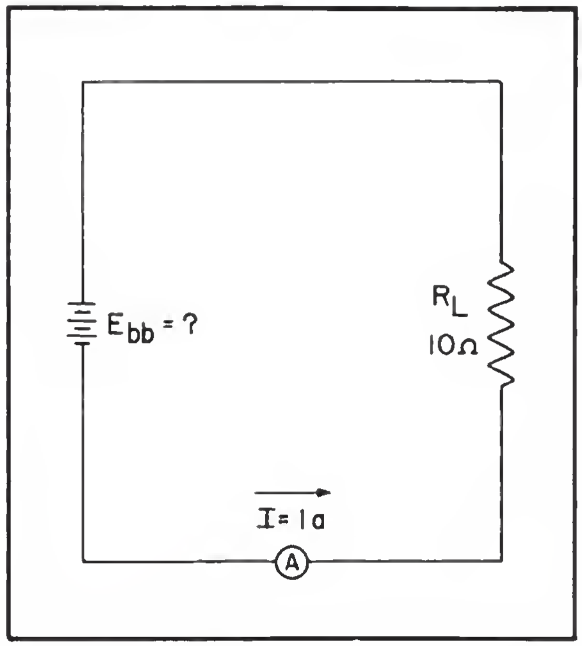


Figure 6-8 - Determining voltage in a basic circuit.

Given: $R = 10$ ohms

$I = 1$ ampere

$E = ?$

Solution:
$$E = IR$$

$$E = 1 \times 10$$

$$E = 10 \text{ volts}$$

Example: When a 10 volt source is connected to a circuit, the circuit draws 5 amperes of current from the source. How much resistance is contained in the circuit?

Given: $E = 10$ volts

$I = 5$ amperes

$R = ?$

Draw and label circuit (Figure 6-9).

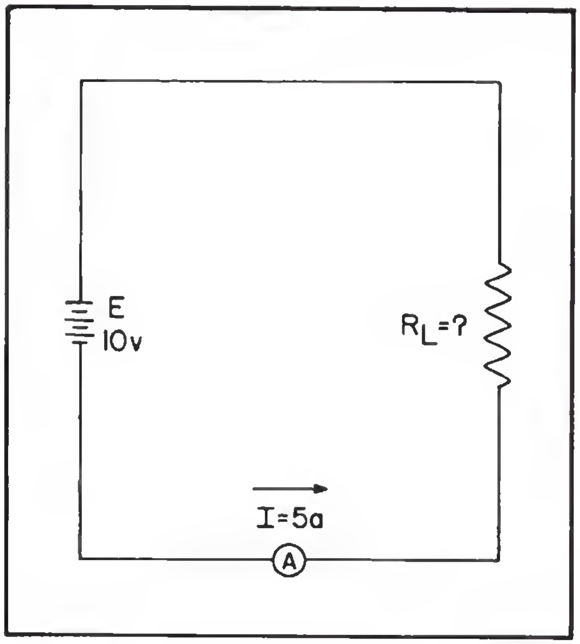


Figure 6-9 - Determining resistance in a basic circuit.

Solution: $R = \frac{E}{I}$ (6-3)

$$R = \frac{10}{5}$$

$R = 2$ ohms

Although the three equations representing Ohm's Law are fairly simple, they are perhaps the most important of all electrical equations. These three equations and the law they represent MUST be THOROUGHLY UNDERSTOOD before continuing on to more advanced theory.

GRAPHICAL ANALYSIS

6-9. Volt-Ampere Characteristic

One of the most valuable methods of inquiry available to the technician is that of graphical analysis. No other method provides a more convenient or more rapid way to observe the characteristics of an electrical device.

The first step in constructing a graph consists of obtaining a table of data from which the graph will evolve. The information in the table can be obtained experimentally by taking laboratory measurements on the device under examination, or can be obtained theoretically through a series of computations. The latter method will be used here.

Let us assume that the characteristics of the circuit shown in Figure 6-10 are to be investigated using Ohm's Law and graphical methods. Since there are three variables (E, I, and R) under consideration, there are three UNIQUE graphs that may be constructed. Only the most common of these three graphs will be demonstrated.

In constructing any graph of electrical quantities,it is standard practice to vary one quantity in a specified way, and note the changes which occur in a second quantity. The quantity which is intentionally varied is called the INDEPENDENT VARIABLE and is plotted on the X-AXIS. The second quantity which changes as a result of changes in the first quantity is called the DEPENDENT VARIABLE and is plotted on the Y-AXIS. Any other quantities involved are held CONSTANT.

In the circuit of Figure 6-10 the resistance will remain fixed (constant) and the voltage (independent variable) will be varied. The resulting changes in current (dependent variable) will then be graphed.

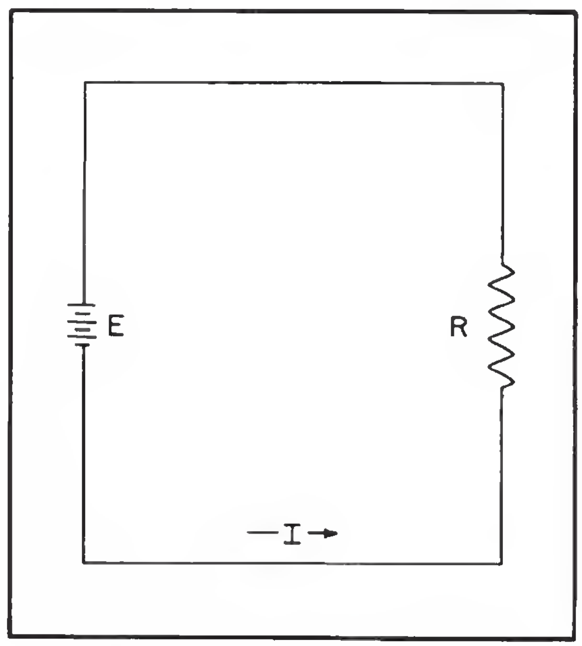


Figure 6-10 - Three variables in a series circuit.

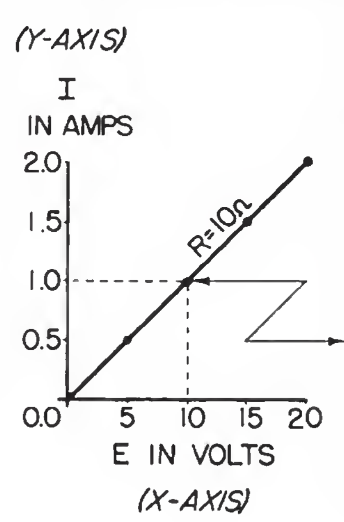
A7. No effect. One change would offset the other.

To aid in compiling the data, a table of values is completed as shown in Figure 6-11. This table shows R to be held constant at 10 ohms as E is varied from 0 to 20 volts in 5 volt steps. Through the use of Ohm's Law the value of current in column two of Table 1 can be calculated for each value of voltage in column one. When the table is complete the information it contains can be used to construct the graph in Figure 6-11. For example, when the voltage applied to the 10 ohm resistor is 10 volts; the current is one ampere. These values of current and voltage determine a point on the graph. When all the points have been plotted, a smooth curve is drawn through the points. This curve is called the VOLT-AMPERE characteristic for the 10 ohm resistor.

Through the use of this curve the value of current through the resistor can be quickly determined for any value of voltage between 0 and 20 volts.

Q8. Using the curve, what value of current will flow through the resistor when 12.5 volts are applied to it?

Q9. Does the value of current determined from the curve agree with the value of current calculated by Ohm's Law?



R=10Ω	
E	I
0	0.0
5	0.5
10	1.0
15	1.5
20	2.0

TABLE I

Figure 6-11 - Volt-ampere characteristic.

A very important characteristic of a fixed resistor is illustrated by the graph in Figure 6-11. Since the volt-ampere characteristic curve is a straight line, it shows that equal changes of voltage across a resistor produce equal changes in current through the resistor. Because of this straight line characteristic the fixed resistor is called a LINEAR device.

ELECTRICAL POWER AND ENERGY

6-10. Power

POWER is the rate of doing work per unit of time. Work results from a force acting on a mass over a distance. The operation of electrical circuits involves a force (voltage) acting on a mass (electrons) over a distance. The amount of time required to perform a given amount of work will determine the power expended. Expressed as an equation, the relationship between power, work, and time is:

$$P = \frac{W}{t} \qquad (6\text{-}4)$$

where: P = power in watts

W = work in joules

t = time in seconds

Since energy is the capacity to do work, power can also be defined as the time rate of developing or expending energy. In every electrical circuit electrical energy is transformed into heat energy. Following the law of conservation of energy, the heat energy will be equal in value to the electrical energy causing it. Therefore, by measuring the amount of heat energy given off by an electrical circuit in a given amount of time, the amount of electrical power consumed in the circuit can be determined.

An experiment measuring the heat given off by an electric circuit was performed by an English physicist, James Joule in 1843. He experimentally proved that the amount of heat produced by an electrical circuit was dependent upon current and resistance. This proportional relationship is known as Joule's Law, and is stated as follows:

LAW 2. The amount of heat produced by a circuit element is directly proportional to resistance, the square of the current, and time.

Expressed as an equation:

$$\text{Heat} = I^2Rt$$

The amount of heat energy produced is equal to the amount of electrical energy consumed, or the amount of work performed.

Therefore: $$\text{Work} = I^2Rt$$

Since: $$P = \frac{W}{t} \qquad (6\text{-}4)$$

$$P = \frac{I^2R\cancel{t}}{\cancel{t}}$$

$$P = I^2R \qquad (6\text{-}5)$$

By substituting Ohm's Law values into the power formula developed from Joule's Law, other equations can be derived that are useful in determining power.

$$P = I^2R \qquad (6\text{-}5)$$

Since: $I = \frac{E}{R}$ $$P = \left(\frac{E}{R}\right)^2R$$

$$P = \frac{E^2}{R^{\cancel{2}}} \times \cancel{R}$$

$$P = \frac{E^2}{R} \qquad (6\text{-}6)$$

The resultant equation (6-6) is useful when the resistance and voltage are known.

The power formula can also be expressed as an equation in terms of current and voltage.

$$P = I^2R \qquad (6\text{-}5)$$

Since: $R = \frac{E}{I}$ $$P = I^2\left(\frac{E}{I}\right)$$

$$P = I^{\cancel{2}}\frac{E}{\cancel{I}}$$

$$P = IE \qquad (6\text{-}7)$$

The unit of measure for electrical power is the WATT. In each of the three derived equations for power, power will be in watts when: E is in volts, I is in amperes, and R is in ohms. As an example: When one volt of potential difference produces a current of one ampere, the power expended is one watt. The watt represents the rate at any given instant at which work is being done in moving electrons through a circuit.

Example: What is the power expended in a circuit when a voltage of 5 volts causes a current of 5 amps as indicated in Figure 6-12?

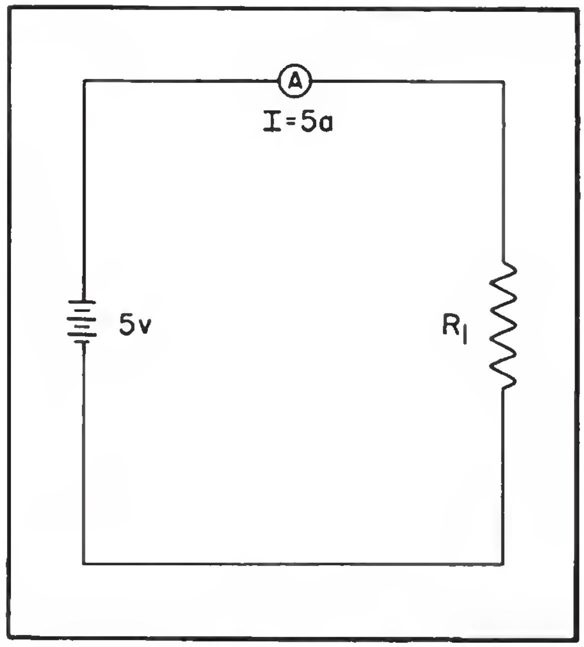


Figure 6-12 - Determining power in a basic circuit.

Given: $I = 5$ amps

$E = 5$ volts

$P = ?$

Solution: $$P = IE \qquad (6\text{-}7)$$

$P = 5$ amps x 5 volts

$P = 25$ watts

Q10. What effect on power is noted when the circuit current increases?

If voltage and resistance are known, as in Figure 6-13, the formula containing voltage and resistance is best suited to compute power.

Given: $E = 5$ volts

$R = 1$ ohm

$P = ?$

Solution: $$P = \frac{E^2}{R} \qquad (6\text{-}6)$$

$$P = \frac{25}{1}$$

$P = 25$ watts

A8. 1.25 amps.

A9. Yes.

A10. With a constant value of resistance, an increase of current increases the power dissipated.

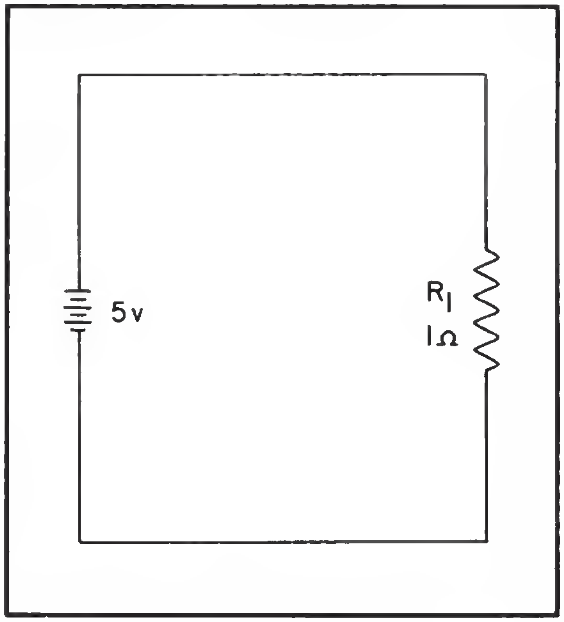


Figure 6-13 - Computing power in a basic circuit.

Q11. What is the effect on power as the applied voltage is decreased?

Had the current and resistance been known as in Figure 6-14, the formula, $P = I^2R$ would apply.

Given: $I = 5$ amps

$R = 1$ ohm

$P = ?$

Solution: $P = I^2R$

$P = (5)^2 1$

$P = 25$ watts

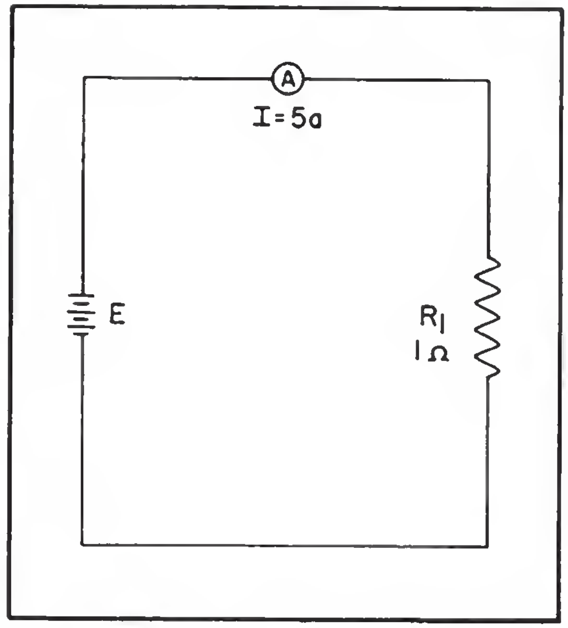


Figure 6-14 - Solving for power in a basic circuit.

Q12. What is the effect on power if the resistance of the circuit in Figure 6-14 is increased? Explain.

The previous examples proved that any form of the power formula can be used to find power in a circuit. Likewise if the power dissipated in a simple circuit is known and the value of any one of the other circuit quantities is known, (E, I, or R), the value of the remaining quantities can be found.

Example. The power dissipated by the 1 ohm resistor in Figure 6-15 is 25 watts. What is the value of current and voltage in the circuit?

Given: $P = 25$ watts

$R = 1$ ohm

$E = ?$

Solve for E: $P = \frac{E^2}{R}$

$E^2 = PR$

$$E = \sqrt{PR} \qquad (6\text{-}8)$$

$E = \sqrt{25 \times 1}$

$E = \sqrt{25}$ or 5 volts

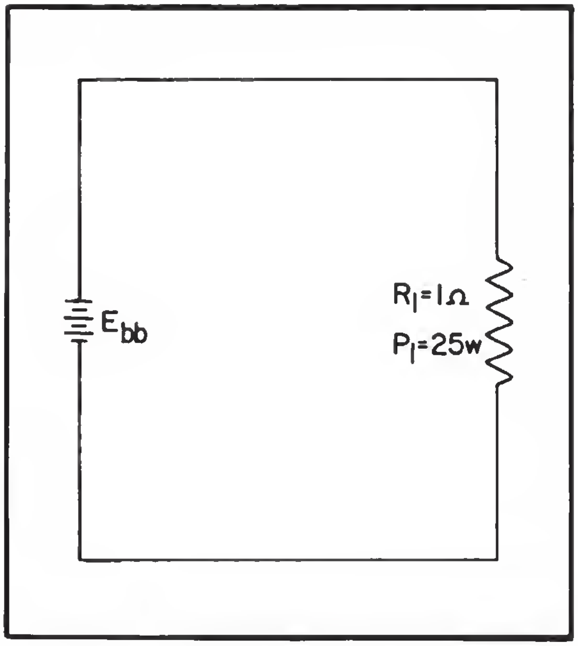


Figure 6-15 - Solving for current and voltage in a basic circuit.

Solve for I: $P = I^2R$

Divide by R

$$\frac{P}{R} = \frac{I^2R}{R}$$

$$\frac{P}{R} = I^2$$

Take the square root of both sides

$$\sqrt{\frac{P}{R}} = I$$

$$I = \sqrt{\frac{P}{R}} \qquad (6\text{-}9)$$

$$I = \sqrt{\frac{25}{1}}$$

$$I = \sqrt{25}$$

$$I = 5 \text{ amps}$$

With a knowledge of transposition of equations, the solution of a simple circuit can be found when any two values are known. Circuits having known values of power and current or power and resistance can be solved similar to the circuit of Figure 6-15 by the correct usage of Joule's Law and Ohm's Law. Always begin a circuit analysis by choosing a formula containing two known values and an unknown that you wish to find.

Q13. The power and the current of a simple circuit are known. It is desired to know the applied voltage. What power formula should be used to solve the problem?

6-11. Power Rating

Electrical components are often given a power rating. The power rating in watts indicates the rate at which the device converts electrical energy into another form of energy such as light, heat, or motion. An example of such a rating is noted when comparing a 150 watt lamp to a 100 watt lamp. The higher wattage rating of the 150 watt lamp indicates it is capable of converting more electrical energy into light energy than the lamp of the lower rating. Other common examples of devices, rated in this manner are soldering irons and small electric motors.

In some electrical devices the wattage rating indicates the maximum power the device is designed to dissipate, rather than the normal operating power. A 150 watt lamp for example dissipates 150 watts when operated at the rated voltage printed on the bulb. In contrast, a device such as a resistor is not normally given a voltage or a current rating. A resistor is

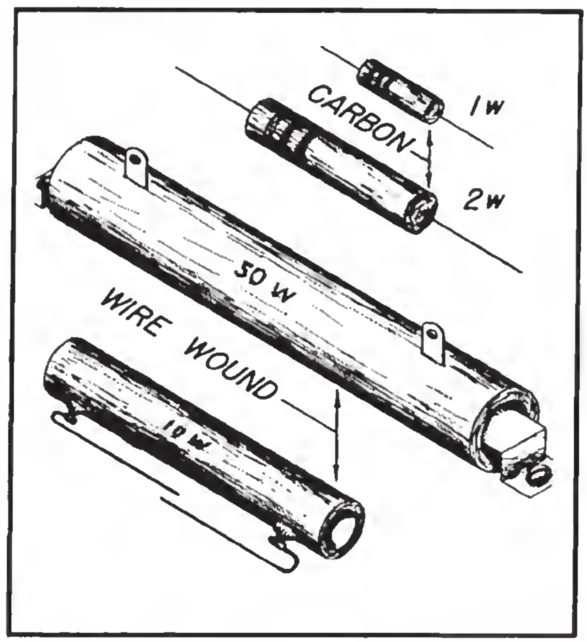


Figure 6-16 - Resistors of different wattage ratings.

A11. Power decreases. P = IE, so if E decreases so does power.

A12. Power decreases. Current decreases with increased resistance. The power changes in proportion to the square of the current change.

A13. P = IE

given a power rating in watts and can be operated at any combination of voltage and current as long as the power rating is not exceeded. In most circuits the actual power dissipated by a resistor will be considerably less than the resistors power rating. In well designed circuits a safety factor of 100% or more is allowed between the actual dissipation of the resistor in the circuit and the power rating listed by the manufacturer. The wattage rating of the resistor is thus the maximum power the resistor can dissipate without damage from overheating.

Resistors of the same resistance value are available in different wattage values. Carbon resistors, for example, are commonly made in wattage ratings of 1/8, 1/4, 1/2, 1, and 2 watts. The larger the physical size of a carbon resistor, the higher its wattage rating, since a larger amount of material will radiate heat more easily.

When resistors of wattage ratings greater than 2 watts are needed, wire-wound resistors are used. Wire-wound resistors are made in sizes between 5 and 200 watts with special types being used for power in excess of 200 watts.

As with other electrical quantities, prefixes may be attached to the word watt when expressing very large or very small amounts of power. Some of the more common of these are: the kilowatt (1000 watts), the megawatt (1,000,000 watts), the milliwatt (1/1,000 of a watt), and the microwatt (1/1,000,000 of a watt).

SERIES CIRCUIT CHARACTERISTICS

6-12. Series Circuits Defined

A SERIES CIRCUIT is defined as a circuit that contains only ONE PATH for current flow. Figure 6-17 shows a comparison between a basic circuit having one lamp and a series circuit having several lamps.

6-13. Series Resistances

Referring to Figure 6-17, the current in a series circuit, in completing its electrical path, must flow through each lamp inserted into the circuit. Thus, each additional lamp offers added resistance. In a series circuit, THE TOTAL CIRCUIT RESISTANCE (R_T) IS EQUAL TO THE SUM OF THE INDIVIDUAL RESISTANCES.

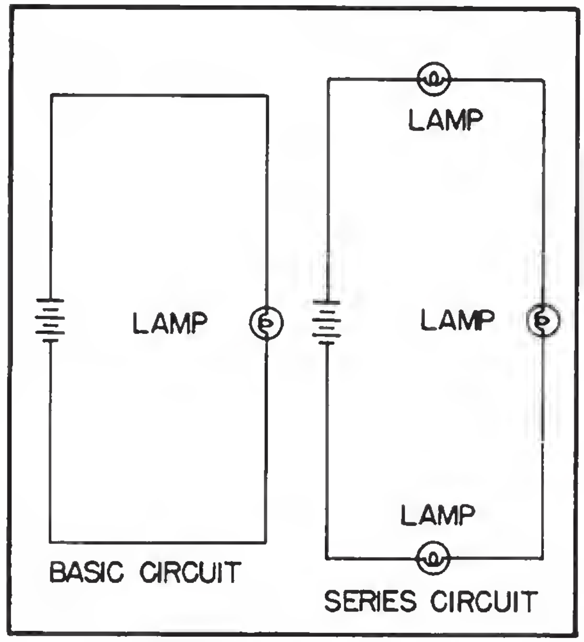


Figure 6-17 - Comparison of basic and series circuits.

As an equation: $R_T = R_1+R_2+R_3+\cdots R_n$ (6-10)

NOTE: The subscript n denotes any number of additional resistances that might be in the equation.

Example: Three resistors of 10 ohms, 15 ohms, and 30 ohms are connected in series across a battery whose EMF is 110 volts (Figure 6-18). What is the total resistance?

Given: R_1 = 10 ohms

R_2 = 15 ohms

R_3 = 30 ohms

R_T = ?

Solution: $R_T = R_1 + R_2 + R_3$

$R_T = 10 + 15 + 30$

R_T = 55 ohms

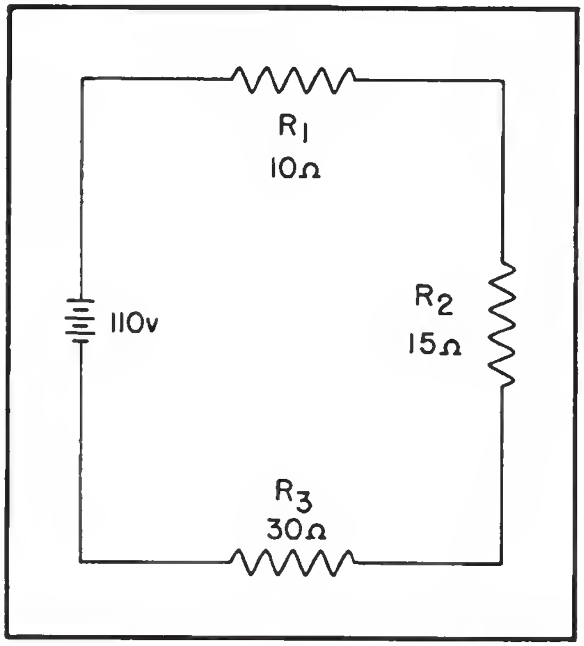


Figure 6-18 - Solving for total resistance in a series circuit

Q14. If the 30 ohm resistor is replaced with two 15 ohm resistors in series, what would be the effect on total circuit resistance?

Q15. If the positions of the battery and resistor R_2 were interchanged, what would be the effect on total resistance,(Figure 6-18)?

In some circuit applications, the total resistance is known and the value of a circuit resistor has to be determined. Equation (6-10) can be transposed to solve for the value of the unknown resistance.

Example: The total resistance of a circuit containing three resistors is 40 ohms (Figure 6-19). Two of the circuit resistors are 10 ohms each. Calculate the value of the third resistor.

Given:

$R_T = 40$ ohms

$R_1 = 10$ ohms

$R_2 = 10$ ohms

$R_3 = ?$

Solution: $$R_T = R_1 + R_2 + R_3 \qquad (6\text{-}10)$$

Subtracting $(R_1 + R_2)$ from both sides of the equation

$$R_3 = R_T - R_1 - R_2$$

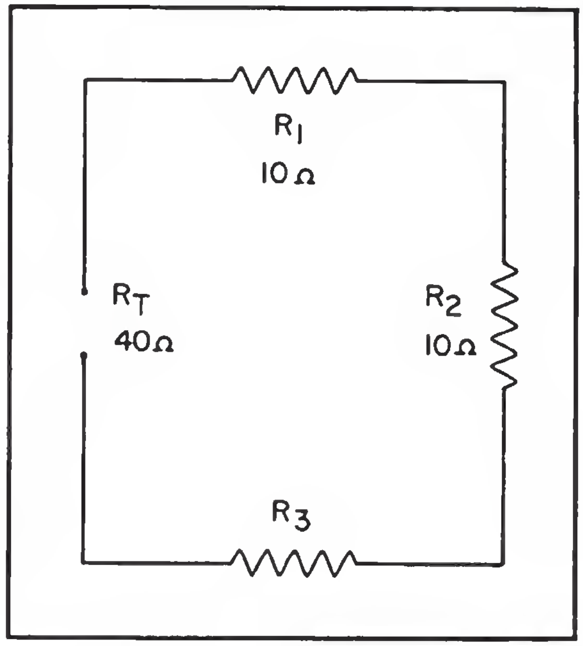


Figure 6-19 - Calculating the value of one resistance in a series circuit.

$$R_3 = R_T - R_1 - R_2$$

$$R_3 = 40 - 10 - 10$$

$$R_3 = 40 - 20$$

$$R_3 = 20 \text{ ohms}$$

6-14. Current

Since there is but one path for current in a series circuit, the same current must flow through each part of the circuit. To determine the current throughout a series circuit, only the current through one of the parts need be known.

The fact that the same current flows through each part of a series circuit can be verified by inserting ammeters into the circuit at various points as shown in Figure 6-20. If this were done, each meter would be found to indicate the same value of current.

Q16. If R_1 of Figure 6-20 is replaced with a smaller resistor, how would the current through R_3 be affected? Explain.

6-15. Series Circuit Voltages

As stated previously, the voltage drop across the resistor in the basic circuit is the total voltage across the circuit and is equal to the

A14. No effect. $R_T = R_1 + R_2 + \cdots R_n$

A15. No effect. $R_T = R_1 + R_2 + R_n$

A16. R_3 current would increase because circuit current has increased. $I = \frac{E}{R}$

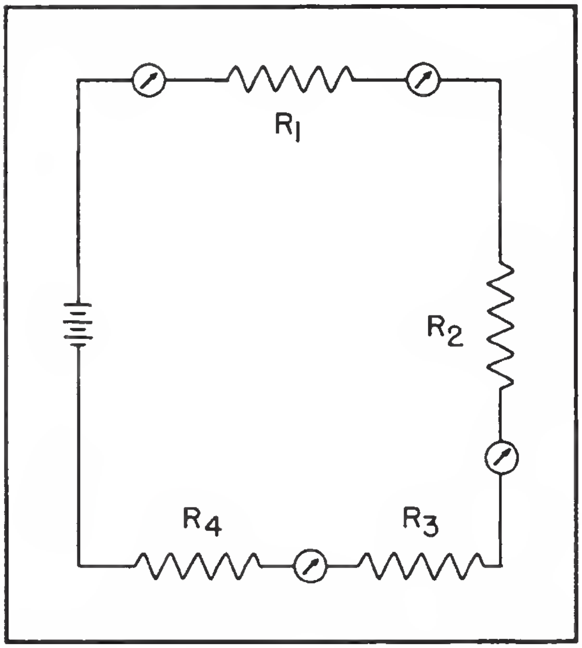


Figure 6-20 - Current in a series circuit.

applied voltage. The total voltage across a series circuit is also equal to the applied voltage, but consists of the sum of two or more individual voltage drops. In any series circuit the SUM of the resistor voltage drops must equal the source voltage. This statement can be proven by an examination of the circuit shown in Figure 6-21. In this circuit a source potential (E_T) of 20 volts is impressed across a series circuit consisting of two 5 ohm resistors. The total resistance of the circuit is equal to the sum of the two individual resistances, or 10 ohms. Using Ohm's Law the circuit current may be calculated as follows:

$$I = \frac{E_T}{R_T}$$

$$I = \frac{20}{10}$$

$$I = 2 \text{ amps}$$

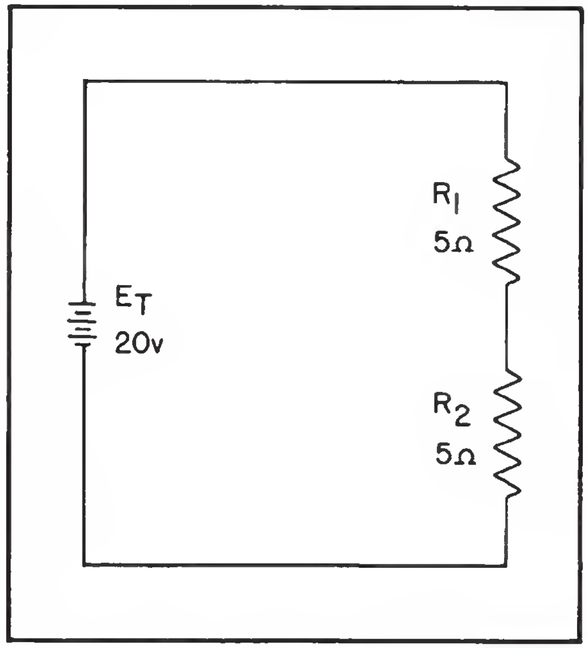


Figure 6-21 - Calculating total resistance in a series circuit.

Knowing the size of the resistors to be 5 ohms each, and the current through the resistors to be 2 amps, the voltage drops across the resistors can be calculated. The voltage (E_1) across R_1 is therefore:

$$E_1 = IR_1$$

$$E_1 = 2 \text{ amps} \times 5 \text{ ohms}$$

$$E_1 = 10 \text{ volts}$$

Since R_2 is the same ohmic value as R_1 and carries the same current, the voltage drop across R_2 is also equal to 10 volts. Adding these two 10 volt drops together gives a total drop of 20 volts exactly equal to the applied voltage. For a series circuit then:

$$E_T = E_1 + E_2 + E_3 + \cdots E_n \qquad (6\text{-}11)$$

Example: A series circuit consists of three resistors having values of 20 ohms, 30 ohms, and 50 ohms respectively. Find the applied voltage if the current through the 30 ohm resistor is 2 amps.

To solve the problem, a circuit diagram is first drawn and labeled (Figure 6-22).

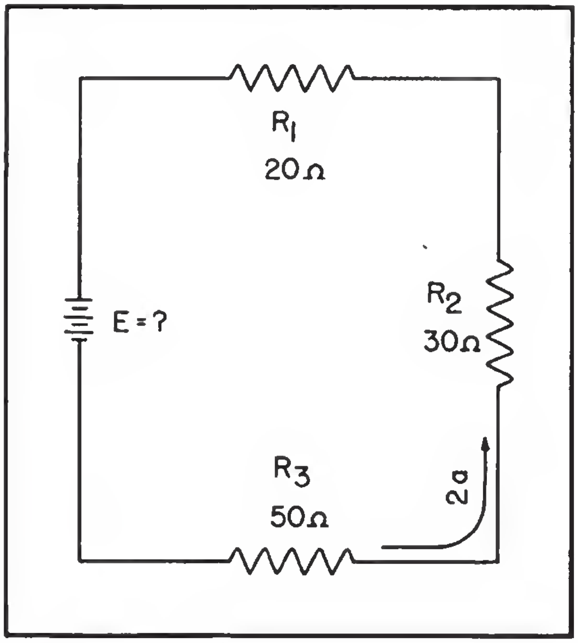


Figure 6-22 - Solving for applied voltage in a series circuit.

Given:

$R_1 = 20$ ohms

$R_2 = 30$ ohms

$R_3 = 50$ ohms

$I = 2$ amps

Solution: Since the circuit involved is a series circuit, the same 2 amps of current flows through each resistor. Using Ohm's Law, the voltage drops across each of the three resistors can be calculated and are:

$E_1 = 40$ volts

$E_2 = 60$ volts

$E_3 = 100$ volts

Once the individual drops are known they can be added to find the total or applied voltage:

$$E_T = E_1 + E_2 + E_3 \qquad (6\text{-}11)$$

$$E_T = 40v + 60v + 100v$$

$$E_T = 200 \text{ volts}$$

NOTE: In using Ohm's Law, the quantities used in the equation MUST be taken from the SAME part of the circuit. In the above example the voltage across R_2 was computed using the current through R_2 and the resistance of R_2.

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It must be emphasized that the potential difference across a resistor remains constant, for it is a measure of the amount of energy required to move a unit charge from one point to another. As long as the source produces electric energy as rapidly as it is consumed in a resistance, the potential difference across the resistance will remain at a constant voltage. The value of this voltage is determined by the applied voltage and the proportional relationship of circuit resistances. The voltage drops that occur in a series circuit are in direct proportions to the resistance across which they appear. This is a result of having the same current flow through each resistor. Thus, the larger the resistor the larger will be the voltage drop across it.

Q17. What would happen to the voltage drops in a series circuit if the applied voltage were to increase?

Q18. What would happen to circuit current in Question 17?

Q19. Describe the effects of reducing the ohmic value of one of the resistors in a series circuit.

6-16. Power

Each of the resistors in a series circuit consumes power which is dissipated in the form of heat. Since this power must come from the source, the total power must be equal in amount to the power consumed by the circuit resistances. In a series circuit the total power is equal to the SUM of the powers dissipated by the individual resistors. Total power (P_T) is thus equal to:

$$P_T = P_1 + P_2 + P_3 + \cdots P_n \qquad (6\text{-}12)$$

Example: A series circuit consists of three resistors having values of 5 ohms, 10 ohms, and 15 ohms. Find the total power dissipation when 120 volts is applied to the circuit. (See Figure 6-23.)

Given:

$R_1 = 5$ ohms

$R_2 = 10$ ohms

$R_3 = 15$ ohms

$E = 120$ volts

A17. They would increase. $E_T = E_1 + E_2 + \cdots E_n$

A18. It would increase.

A19. The total resistance would decrease, the current would increase, and the voltage drops across the other resistors would increase.

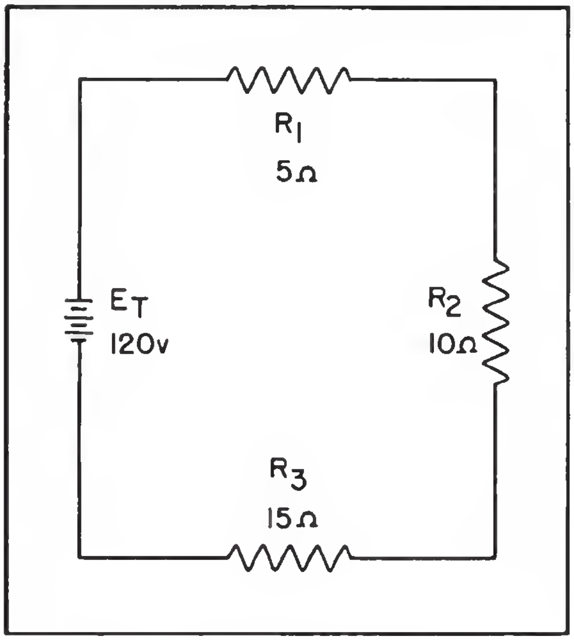


Figure 6-23 - Solving for total power in a series circuit.

Solution: The total resistance is found first.

$$R_T = R_1 + R_2 + R_3 \qquad (6\text{-}10)$$

$$R_T = 5 + 10 + 15$$

$$R_T = 30 \text{ ohms}$$

Using total resistance and the applied voltage, the circuit current is calculated.

$$I = \frac{E_T}{R_T}$$

$$I = \frac{120}{30}$$

$$I = 4 \text{ amps}$$

Using the power formulas, the individual power dissipations can be calculated. For resistor R_1:

$$P_1 = I^2 R_1 \qquad (6\text{-}5)$$

$$P_1 = (4)^2 5$$

$$P_1 = 80 \text{ watts}$$

For R_2:

$$P_2 = I^2 R_2 \qquad (6\text{-}5)$$

$$P_2 = (4)^2 10$$

$$P_2 = 160 \text{ watts}$$

For R_3:

$$P_3 = I^2 R_3 \qquad (6\text{-}5)$$

$$P_3 = (4)^2 15$$

$$P_3 = 240 \text{ watts}$$

To obtain total power:

$$P_T = P_1 + P_2 + P_3 \qquad (6\text{-}12)$$

$$P_T = 80 + 160 + 240$$

$$P_T = 480 \text{ watts}$$

To check the answer the total power delivered by the source can be calculated:

$$P_{source} = I_{source} \times E_{source} \qquad (6\text{-}7)$$

$$P_{source} = 4 \text{ a} \times 120 \text{ v}$$

$$P_{source} = 480 \text{ watts}$$

Thus the total power is equal to the sum of the individual power dissipations.

Q20. What happens to total power if the source voltage is doubled?

6-17. Summary of Characteristics

The important factors governing the operation of a series circuit are listed below. These factors have been set up as a group of rules so that they may be easily studied. These rules must be completely understood before the study of more advanced circuit theory is undertaken.

RULES FOR SERIES DC CIRCUITS

1. The same current flows through each part of a series circuit.

2. The total resistance of a series circuit is equal to the sum of the individual resistances.

3. The total voltage across a series circuit is equal to the sum of the individual voltage drops.

4. The voltage drop across a resistor in a series circuit is proportional to the size of the resistor.

5. The total power dissipated in a series circuit is equal to the sum of the individual power dissipations.

GENERAL CIRCUIT ANALYSIS

6-18. A Complete Solution

To establish a procedure for solving series circuits, the following sample problem will be solved.

Example: Three resistors of 5 kilohms, 10 kilohms, and 15 kilohms are connected across a battery rated at 90 volts terminal voltage. Completely solve the circuit (Figure 6-24).

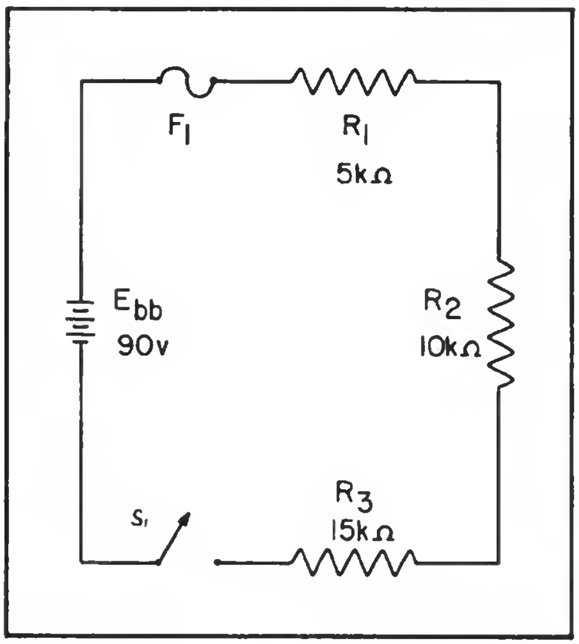


Figure 6-24 - Solving for various values in a series circuit.

In solving the circuit the total resistance will be found first. Next, the circuit current will be calculated. Once the current is known the voltage drops and power dissipations can be calculated.

The total resistance is:

$$R_T = R_1 + R_2 + R_3$$

$$R_T = 5k + 10k + 15k$$

$$R_T = 30 \text{ kilohms}$$

By Ohm's Law the current is:

$$I = \frac{E_{bb}}{R_T}$$

$$I = \frac{90}{30,000}$$

$$I = 0.003 \text{ amp or } 3 \text{ milliamps}$$

The voltage (E_1) across R_1 is:

$$E_1 = IR_1$$

$$E_1 = 3 \text{ ma} \times 5k$$

$$E_1 = 15 \text{ volts}$$

The voltage (E_2) across R_2 is:

$$E_2 = IR_2$$

$$E_2 = 3 \text{ ma} \times 10k$$

$$E_2 = 30 \text{ volts}$$

The voltage (E_3) across R_3 is:

$$E_3 = IR_3$$

$$E_3 = 3 \text{ ma} \times 15k$$

$$E_3 = 45 \text{ volts}$$

The power dissipated in R_1 is:

$$P_1 = I \times E_1$$

$$P_1 = 3 \text{ ma} \times 15v$$

$$P_1 = 0.045 \text{ watt or } 45 \text{ milliwatts}$$

The power dissipated in R_2 is:

$$P_2 = I \times E_2$$

$$P_2 = 3 \text{ ma} \times 30v$$

$$P_2 = 0.09 \text{ watt or } 90 \text{ milliwatts}$$

A20. Total power increases to four times its original value. $P = \frac{E^2}{R}$

The power dissipated in R3 is:

$P_3 = I \times E_3$

$P_3 = 3\text{ ma} \times 45\text{v}$

$P_3 = 0.135$ watt or 135 milliwatts

The total power dissipated is:

$P_T = E_T \times I$

$P_T = 90 \times 3\text{ ma}$

$P_T = 0.27$ watt or 270 milliwatts

Example: Four resistors $R_1 = 10$ ohms, $R_2 = 10$ ohms, $R_3 = 50$ ohms, and $R_4 = 30$ ohms are connected in series across a battery. The current through the circuit is 1/2 ampere. (Figure 6-25)

a. What is the battery voltage?
b. What is the voltage across each resistor?
c. What is the power expended in each resistor?
d. What is the total power?

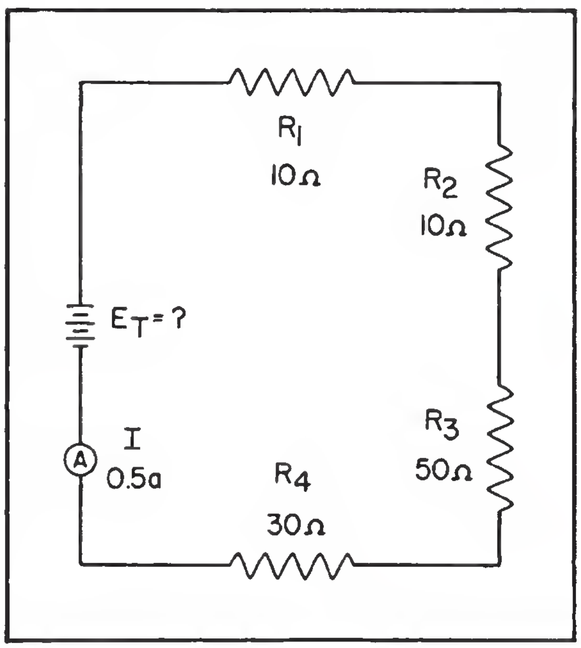


Figure 6-25 - Computing series circuit values

Given: $R_1 = 10$ ohms

$R_2 = 10$ ohms

$R_3 = 50$ ohms

$R_4 = 30$ ohms

$I = 0.5$ amp

Find:

$E_1 = ?$	$P_1 = ?$
$E_2 = ?$	$P_2 = ?$
$E_3 = ?$	$P_3 = ?$
$E_4 = ?$	$P_4 = ?$
$E_T = ?$	$P_T = ?$

Solution:

(a) $R_T = R_1 + R_2 + R_3 + R_4$

$R_T = 10 + 10 + 50 + 30 = 100$ ohms

$E_T = IR_T = 0.5 \times 100 = 50$ volts

(b) $E_1 = IR_1 = 0.5 \times 10 = 5$ volts

$E_2 = IR_2 = 0.5 \times 10 = 5$ volts

$E_3 = IR_3 = 0.5 \times 50 = 25$ volts

$E_4 = IR_4 = 0.5 \times 30 = 15$ volts

Check: $E_T = E_1 + E_2 + E_3 + E_4$

$E_T = 5 + 5 + 25 + 15 = 50$ volts

(c) Power consumed in R_1 is:

$P_1 = IE_1 = 0.5 \times 5 = 2.5$ watts

$P_2 = IE_2 = 0.5 \times 5 = 2.5$ watts

$P_3 = IE_3 = 0.5 \times 25 = 12.5$ watts

$P_4 = IE_4 = 0.5 \times 15 = 7.5$ watts

(d) Total power -

$P_T = P_1 + P_2 + P_3 + P_4$

$P_T = 2.5 + 2.5 + 12.5 + 7.5 = 25$ watts

Check:

$$P_T = I_T^2R_T = 0.5^2 \times 100 = 25 \text{ watts}$$

or: $$P_T = I_TE_T = 0.5 \times 50 = 25 \text{ watts}$$

or: $$P_T = \frac{E_T^2}{R_T} = \frac{50^2}{100} = \frac{2500}{100} = 25 \text{ watts}$$

An important fact to keep in mind when applying Ohm's Law to a series circuit is to consider whether the values used are component values or total values. When the information available enables the use of Ohm's Law to find total resistance, total voltage and total current, total values must be inserted into the formula.

To find total resistance:

$$R_T = \frac{E_T}{I_T}$$

To find total voltage:

$$E_T = I_T \times R_T$$

To find total current:

$$I_T = \frac{E_T}{R_T}$$

NOTE: I_T is equal to I in a series circuit. However, the distinction between I_T and I in the formula should be noted. The reason being that future circuits may have several currents, and it will be necessary to differentiate between I_T and other currents.

To compute any quantity (E, I, R, or P) associated with a single given resistor, the values used in the formula must be obtained from that particular resistor. For example, to find the value of an unknown resistance, the voltage across and the current through that particular resistor must be used.

To find the value of a resistor:

$$R = \frac{E_R}{I_R}$$

To find the voltage drop across a resistor:

$$E_R = I_R \times R$$

To find current through a resistor:

$$I_R = \frac{E_R}{R}$$

KIRCHHOFF'S VOLTAGE LAW

6-19. Kirchhoff's Second Law

In 1847 Kirchhoff extended the use of Ohm's Law by developing a simple concept concerning the voltages contained in a series circuit loop. Kirchhoff's Law is stated as:

LAW 3. The algebraic sum of the instantaneous E.M.F's and voltage drops around any closed circuit loop is zero.

Through the use of Kirchhoff's Law, circuit problems can be solved which would be difficult and often impossible with only a knowledge of Ohm's Law. When the law is properly applied, an equation can be set up for a closed loop and the unknown circuit values may be calculated.

6-20. Polarity of Voltage

To apply Kirchhoff's Voltage Law, the meaning of voltage POLARITY must be understood. In the circuit shown in Figure 6-26 the current is seen to be flowing in a counter-clockwise direction due to the arrangement of the battery source E_{bb}. Notice that the end of resistor R_1 into which the current flows is marked NEGATIVE (-). The end of R_1 at which the current leaves is marked POSITIVE (+). These polarity markings are used to show that the end of R_1 into which the current flows is at a higher negative potential than is the end of the resistor at which the current leaves. Point (A) is thus more negative than point (B).

Point (C), which is at the same potential as point (B), is labeled negative. This is to indicate that point (C), though positive with respect to point (A), is more negative than point (D). To say a point is positive (or negative), without stating what it is positive IN RESPECT TO, has no meaning.

Q21. What is the polarity of point (D) with respect to point (B) in Figure 6-26?

A21. Positive. Point D is positive with respect to point C by the amount of voltage drop across R_2.

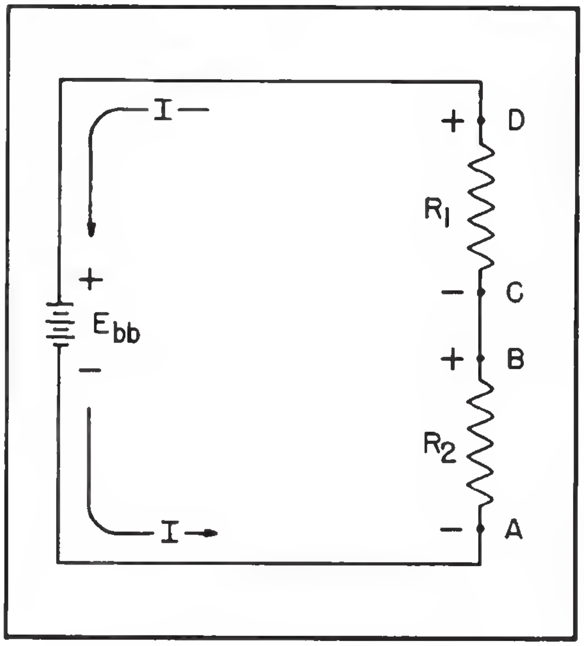


Figure 6-26 - Voltage polarities.

6-21. Application of Kirchhoff's Voltage Law

Kirchhoff's Law, stated as LAW 3, can be written as an equation as shown below:

$$E_a + E_b + E_c + \cdots E_n = 0 \qquad (6\text{-}13)$$

where E_a, E_b, etc., are the voltage drops and E.M.F.'s around any closed circuit loop. To set up the equation for an actual circuit, the following procedure is used.

1. Assume a direction of current through the circuit. (Correct direction desirable but not necessary.)

2. Using assumed direction of current, assign polarities to all resistors through which the current flows.

3. Place correct polarities on any sources included in the circuit.

4. Starting at any points in the circuit, trace around the circuit writing down the magnitude and polarity of the voltage across each component in succession. The polarity used is the sign AFTER the component is passed through. Stop when reaching the point at which the trace was started.

5. Place these voltages with their polarities into equation (6-13) and solve for the desired quantity.

Example: Three resistors are connected across a 50 volt source. What is the voltage across the third resistor if the voltage drops across the first two resistors are 25 volts and 15 volts?

Solution: A diagram is first drawn as shown in Figure 6-27. Next a direction of current is assumed as shown. Using this current, the po-

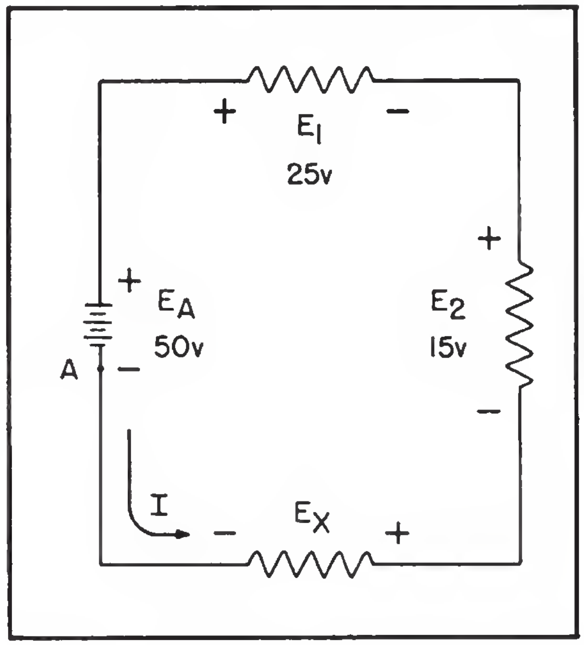


Figure 6-27 - Determining unknown voltage in a series circuit.

larity markings are placed at each end of each resistor and also on the terminals of the source. Starting at point (A), trace around the circuit in the direction of current flow recording the voltage and polarity of each component. Starting at point (A) these voltages would be as follows:

Basic formula:

$$E_a + E_b + E_c \cdots E_n = 0 \qquad (6\text{-}13)$$

From the circuit:

$$(+E_x) + (+E_2) + (+E_1) + (-E_A) = 0$$

Substituting values from circuit:

$$E_x + 15 + 25 - 50 = 0$$

$$E_x - 10 = 0$$

$$E_x = 10 \text{ volts}$$

Thus, the unknown voltage (E_x) is found to be 10 volts.

Using the same idea as above, a problem can be solved in which the current is the unknown quantity.

Example: A circuit having a source voltage of 60 volts contains three resistors of 5 ohms, 10 ohms, and 15 ohms. Find the circuit current.

Solution: Draw and label the circuit (Figure 6-28). Establish a direction of current flow and assign polarities. Next, starting at any point, point (A) will be chosen in this example; write out the loop equation.

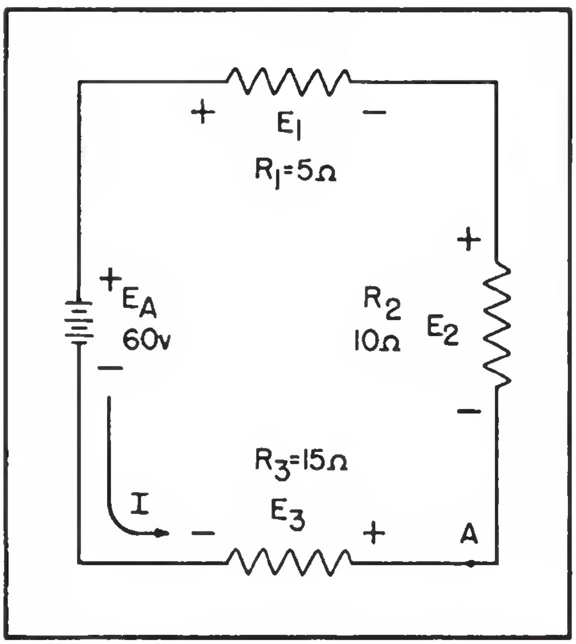


Figure 6-28 - Correct direction of assumed current.

Basic equation:

$$E_a + E_b + E_c + \dots E_n = 0 \qquad (6\text{-}13)$$

$$+E_2 + E_1 - E_A + E_3 = 0$$

Since E = IR, by substitution:

$$IR_2 + IR_1 - E_A + IR_3 = 0$$

Substituting values:

$$10I + 5I - 60 + 15I = 0$$

Combining like terms:

$$30I - 60 = 0$$

$$30I = 60$$

$$I = 2 \text{ amps}$$

Since the current obtained in the above calculations is a positive 2 amps, the assumed direction of current was correct. To show what happens if the incorrect direction of current is assumed, the problem will be solved as before but with the opposite direction of current. The circuit is redrawn showing the new direction of current and new polarities in Figure 6-29.

Solution:

$$E_a + E_b + E_c + \dots E_n = 0 \qquad (6\text{-}13)$$

Starting at point (A):

$$-E_2 - E_1 - E_A - E_3 = 0$$

$$-IR_2 - IR_1 - E_A - IR_3 = 0$$

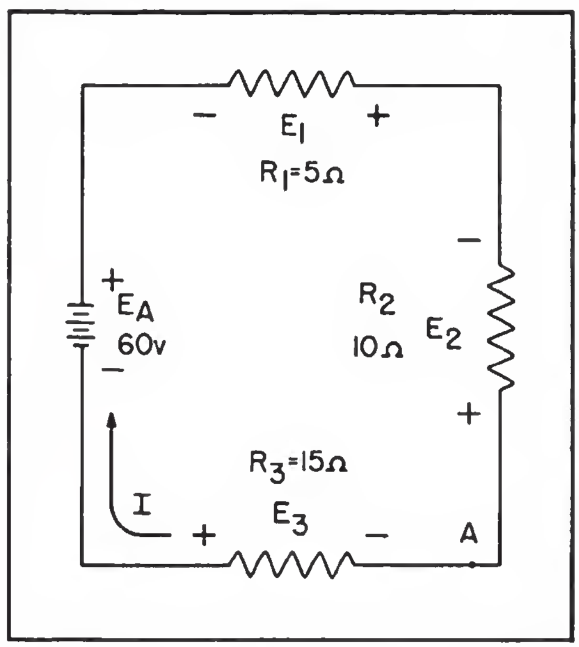


Figure 6-29 - Incorrect direction of assumed current.

$$10I - 5I - 60 - 15I = 0$$

$$-30I - 60 = 0$$

$$-30I = 60$$

$$I = -2 \text{ amps}$$

Notice that the AMOUNT of current is the SAME as before. Its polarity, however, is NEGATIVE. The negative polarity simply indicates the wrong direction of current was assumed. Should it be necessary to use this current in further calculations on the circuit, the negative polarity should be retained in the calculations.

6-22. Series Aiding and Opposing Sources

In many practical applications a circuit may contain more than one source. Sources of E.M.F. that cause current to flow in the same direction are considered to be SERIES AIDING and their voltages add. Sources of E.M.F. that would tend to force current in opposite directions are said to be SERIES OPPOSING, and the effective source voltage is the difference between the opposing voltages. When two opposing sources are inserted into a circuit, current flow would be in a direction determined by the larger source. Examples of series aiding and opposing sources are shown in Figure 6-30.

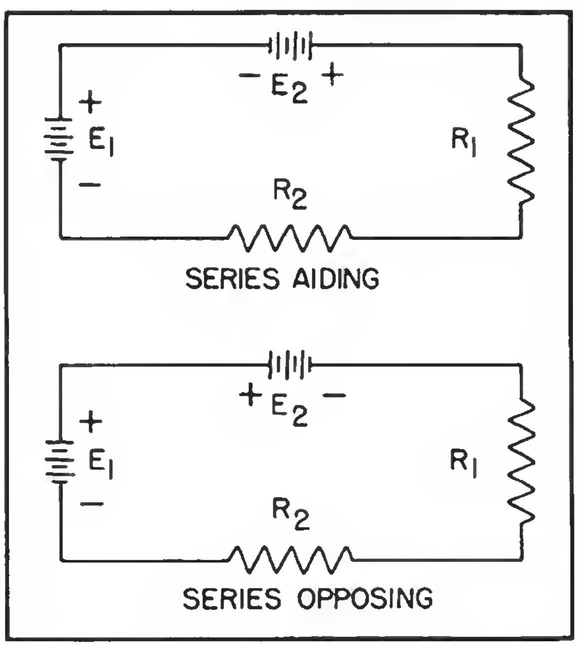


Figure 6-30 - Aiding and opposing sources.

Q22. Assuming the circuit to be energized, would it be possible to have a complete electrical circuit but have no current flow? Explain.

6-23. Multiple Source Solutions

A simple solution may be obtained for a multiple source circuit through the use of Kirchhoff's Voltage Law. In applying this method, the exact same procedure is used for the multiple source as was used above for the single source circuit. This is demonstrated by the following problem.

Example: Using Kirchhoff's Voltage equation, find the amount of current in the circuit shown in Figure 6-31.

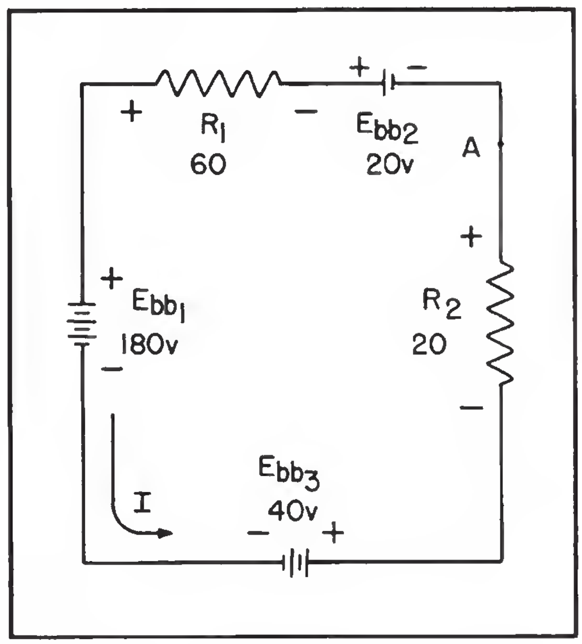


Figure 6-31 - Solving for circuit current using Kirchhoff's voltage equation.

Solution: As before, a direction of current flow is assumed and polarity signs are placed on the drawing. The loop equation will be starting at point (A).

Basic equation: $E_a + E_b + E_c + \cdots\cdots E_n = 0$ (6-13)

From the circuit:

$$E_{bb2} + E_1 - E_{bb1} + E_{bb3} + E_2 = 0$$

$$+20 + 60I - 180 + 40 + 20I = 0$$

Combining like terms:

$$+80I - 120 = 0$$

$$80I = 120$$

$$I = 1.5 \text{ amps}$$

Q23. State which sources are series aiding and which ones are series opposing in Figure 6-31.

VOLTAGE REFERENCES

6-24. Reference Points

A REFERENCE POINT is an arbitrarily chosen point to which all other points are compared. In series circuits, any point can be chosen as a reference and the electrical potential at all other points can be determined in reference to the initial point. In the example of Figure 6-32 point (A) shall be considered as

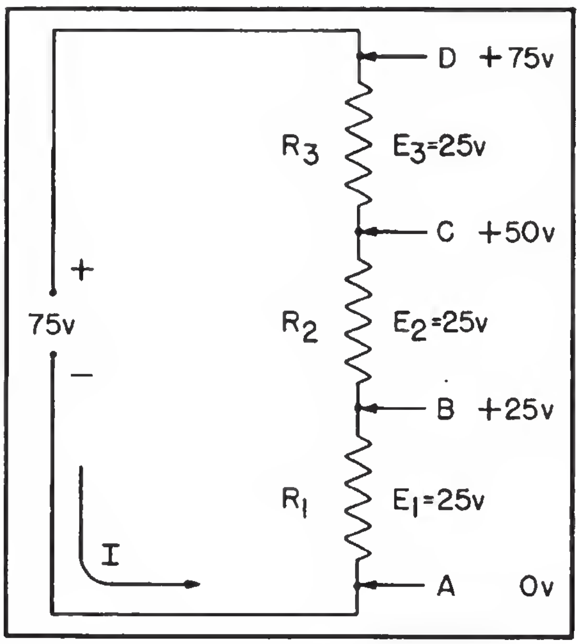


Figure 6-32 - Reference points in a series circuit.

the reference. Each series resistor in the illustrated circuit is of equal value; therefore, the applied voltage is equally distributed across each resistor. The potential at point (B) is 25 volts more positive than (A). Points (C) and (D) are 50 volts and 75 volts respectively more positive than point (A).

If point (B) is used as the reference as in Figure 6-33, point (D) would be positive 50 volts in respect to the new reference point (B). The former reference point (A) is twenty-five volts negative in respect to point (B).

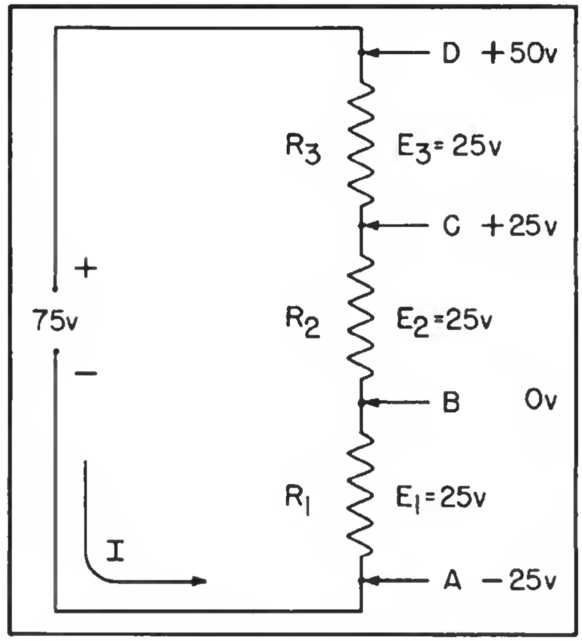


Figure 6-33 - Determining potentials with respect to a reference point.

Q24. What is the voltage at point (C) in reference to point (D)?

6-25. Ground

As in the previous circuit illustration, the reference point of a circuit is always considered to be at zero potential. Since the earth (ground) is said to be at a zero potential, the term GROUND is used to denote a common electrical point of zero potential. In the following illustration, Figure 6-34, point (A) is the zero reference or ground and is symbolized as such.

Point (C) is 75 volts positive and point (B) is 25 volts positive in respect to ground.

In most electronic equipment, the metal chassis is the common ground for the many electrical circuits. The value of ground is noted when considering its contribution to economy, simplification of schematics, and ease of measurement. When completing each electrical circuit, common points of a circuit at zero potential are connected directly to the metal chassis thereby eliminating a large amount of connecting wire. The electrons pass through the metal chassis (conductor) to reach other points of the circuit. An example of a grounded circuit is illustrated in Figure 6-35.

A22. Yes, by using series opposing batteries that exactly balance each other.

A23. E_2 and E_3 are series aiding to each other, and series opposing to E_1.

A24. Point (C) is 25 volts negative with respect to (D).

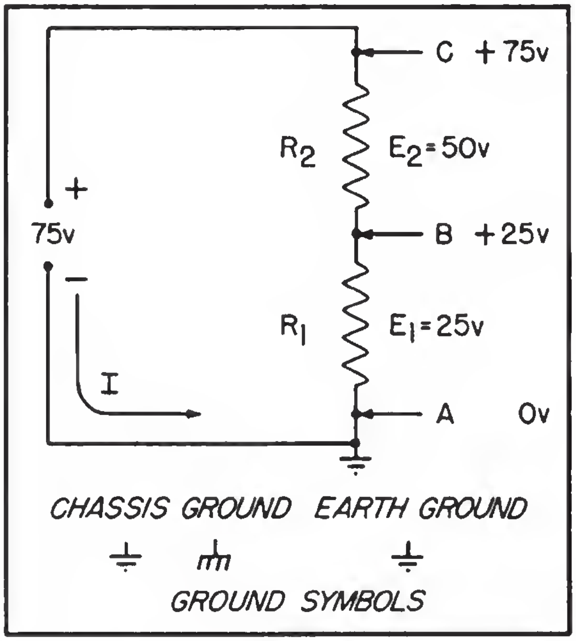


Figure 6-34 - Use of ground symbols.

Most voltage measurements used to check proper circuit operation in electronic equipment are taken in respect to ground. One meter lead is attached to ground and the other meter lead is moved to various test points.

OPEN AND SHORT CIRCUITS

6-26. Open Circuits

A circuit is said to be OPEN when a break exists in a complete conducting pathway. Although an open occurs any time a switch is thrown to deenergize a circuit, an open may also develop accidentally due to abnormal circuit conditions. To restore a circuit to proper operation, the open must be located and its cause determined.

Sometimes an open can be located visually by a close inspection of the circuit components. Defective components, such as burned out resistors and fuses can usually be discovered by

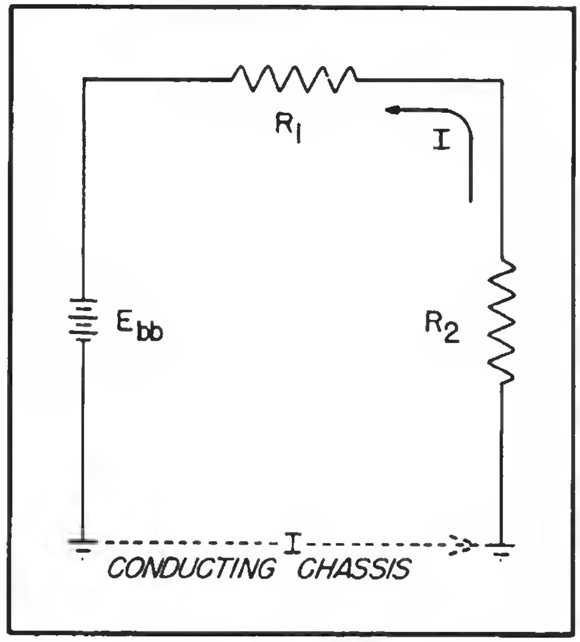


Figure 6-35 - Ground used as a conductor.

this method. Others such as a break in wire covered by insulation, or the melted element of an enclosed fuse, are not visible to the eye. Under such conditions, the understanding of an open's effect on circuit conditions enables a

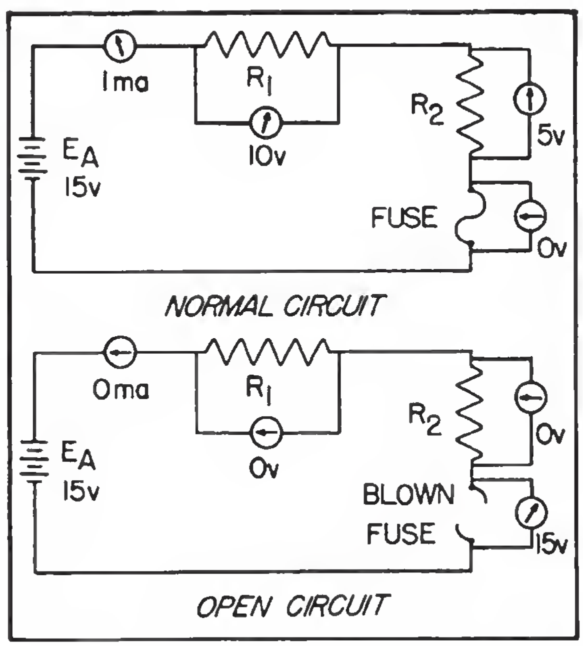


Figure 6-36 - Normal and open circuit conditions.

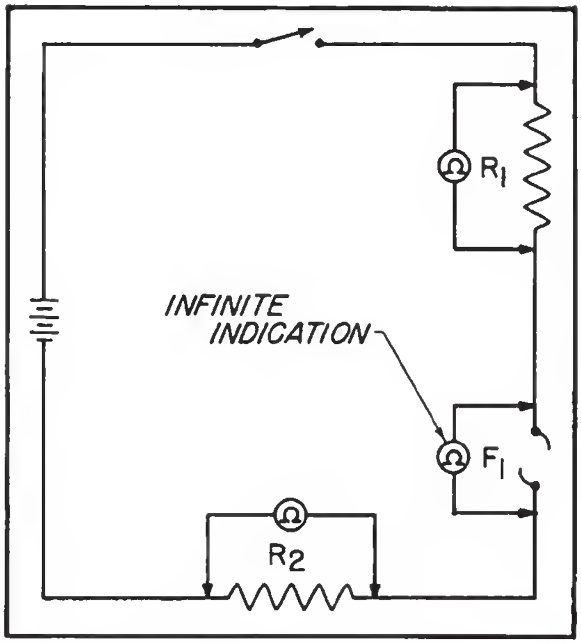


Figure 6-37 - Ohmmeter readings in a series circuit.

technician to make use of a voltmeter or ohmmeter to locate the open component.

In Figure 6-36, the series circuit consists of two resistors and a fuse. Notice the effects on circuit conditions when the fuse opens.

Current ceases to flow; therefore, there is no longer a voltage drop across the resistors. Each end of the open conducting path becomes an extension of the battery terminals and the voltage felt across the open is equal to the applied voltage.

An open circuit, such as found in Figure 6-36 could also have been located with an ohmmeter. However, when using an ohmmeter to check a circuit, it is important to first deenergize the circuit. The reason being that an ohmmeter has its own power source and would be damaged if connected to an energized circuit.

The ohmmeter used to check a series circuit would indicate the ohmic value of each resistance it is connected across. The open circuit due to its almost infinite resistance would cause no deflection on the ohmmeter as indicated by the illustration, Figure 6-37.

6-27. Short Circuits

A SHORT CIRCUIT is an accidental path of low resistance which passes an abnormal amount of current. A short circuit exists whenever the resistance of the circuit or the resistance of a part of a circuit drops in value to almost zero ohms. A short often occurs as a result of improper wiring or broken insulation.

In Figure 6-38 a short is caused by improper wiring. Note the effect on current flow. Since the resistor has in effect been replaced with a piece of wire, practically all the current flows through the short and very little current flows through the resistor. Electrons flow through the short, a path of almost zero resistance and complete the circuit by passing through the ten ohm resistor and the battery. The amount of current flow increases greatly because its resistive path has decreased from ten thousand and ten ohms to ten ohms. Due to the excessive current through the ten ohm resistor, the increased heat dissipated by the resistor will destroy the component.

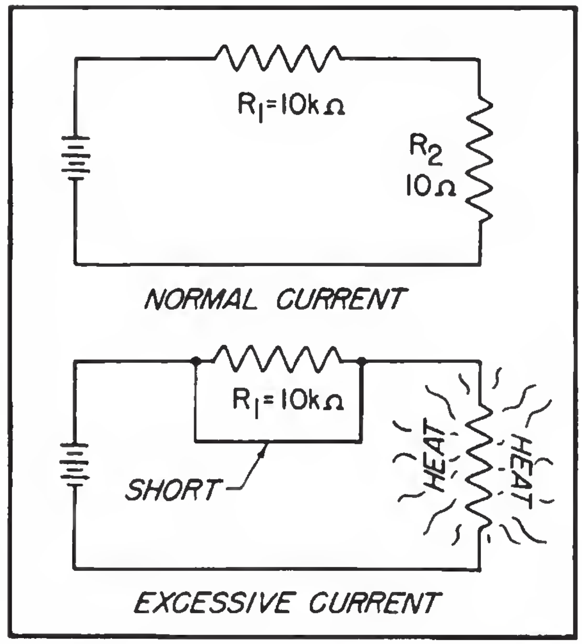


Figure 6-38 - Normal and short circuit conditions.

The illustration in Figure 6-39 shows a pictorial wiring diagram rather than a schematic diagram to indicate how broken insulation might cause a short circuit.

Q25. What is indicated, if an ohmmeter connected across a fuse reads a short circuit?

A25. Normal condition. Most fuses have a resistance too low to read with the average ohmmeter.

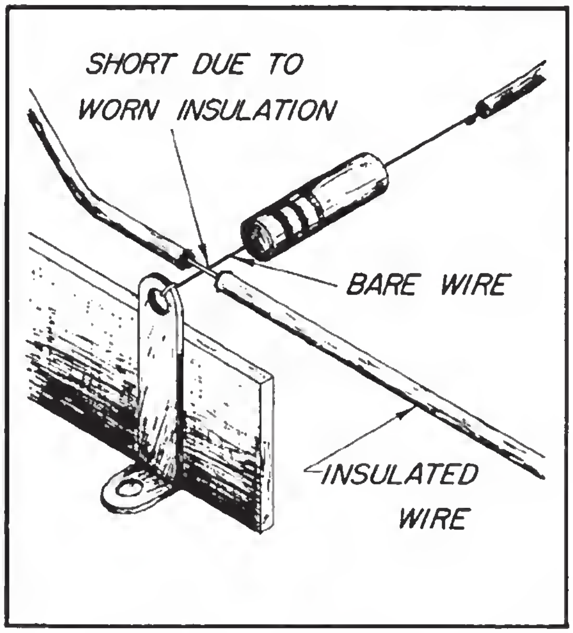


Figure 6-39 - Short due to broken insulation.

SOURCE RESISTANCE, POWER TRANSFER AND CIRCUIT EFFICIENCY

6-28. Source Resistance

A voltmeter connected across the terminals of a good 1.5 volt dry cell will read about 1.5 volts. If the same cell is inserted into a complete circuit, the voltmeter reading will decrease to something less than the previous 1.5 volts. This difference in terminal voltage is attributed to a cell's INTERNAL RESISTANCE, the opposition to current offered by the cell's electrolyte. All sources of electromotive force have some form of internal resistance which causes a drop in terminal voltage as current flows through the source. The decrease in terminal voltage can be attributed to the voltage drop across the internal resistance.

This principle is illustrated in Figure 6-40 where the internal resistance of a battery is shown. In the schematic the internal resistance is indicated by an additional resistor in series with the battery. The battery with its internal resistance is enclosed within the dotted lines of the schematic diagram. With the switch open, the voltage across the battery terminals reads 15 volts. As the switch is closed, current flow causes voltage drops around the circuit. The circuit current of two amperes causes a voltage drop of 2 volts across R_1, the one ohm internal battery resistance thereby drops the battery terminal voltage to 13 volts. Internal resistance cannot be measured with an ohmmeter. An attempt to do this would damage the meter.

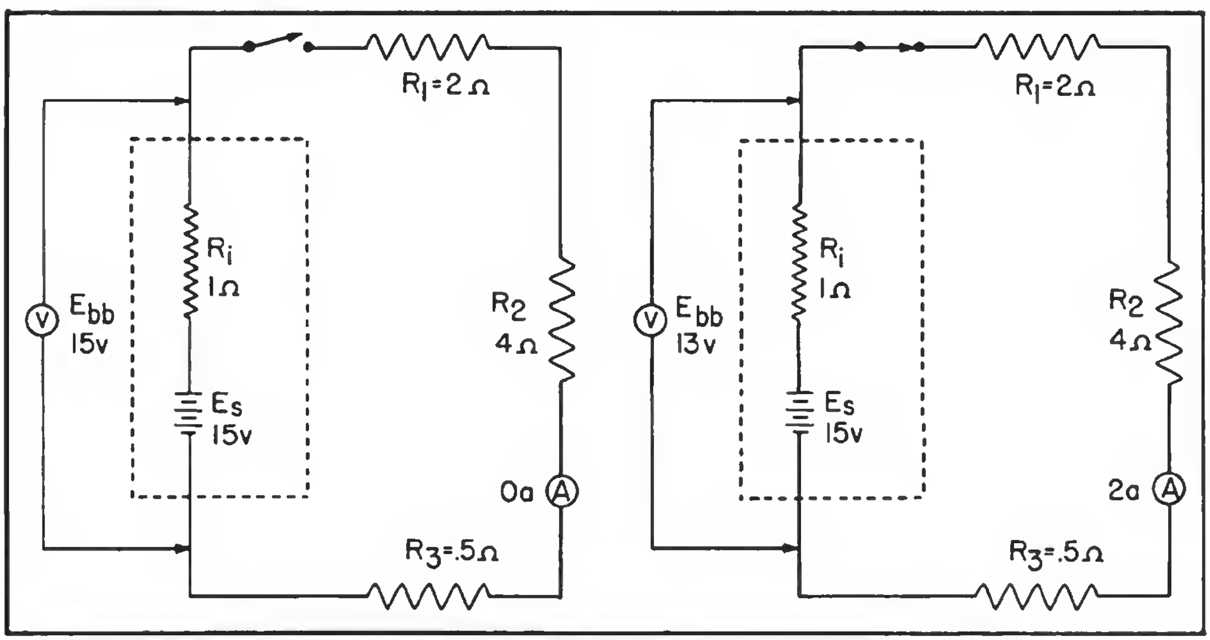


Figure 6-40 - Effect of internal resistance.

6-29. Power Transfer and Circuit Efficiency

The effect of the source resistance on the power output of a dc source may be shown by an analysis of the circuit in Figure 6-41(A). When the variable load resistor, R_L, is set at the zero ohms position (equivalent to a short circuit) the circuit is limited only by the internal resistance, R_i, of the source. The short circuit current, I, is determined as:

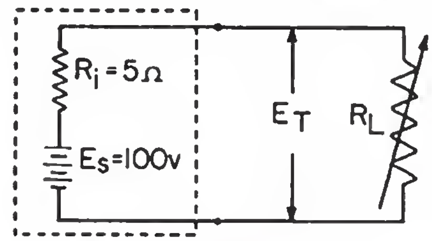
$$I = \frac{E_s}{R_i} = \frac{100}{5} = 20 \text{ amperes}$$

This is the maximum current that may be drawn from the source. The terminal voltage across the short circuit is zero and all the voltage is dropped across the resistance within the source.

If the load resistance, R_L, is increased (the internal resistance remaining the same), the current drawn from the source will decrease. Consequently, the voltage drop across the internal resistance will decrease. At the same time, the terminal voltage applied across the load will increase and will approach a maximum as the current approaches zero.

The MAXIMUM POWER TRANSFER THEOREM says in effect that maximum power is transferred from the source to the load when the resistance of the load is equal to the internal resistance of the source. This theorem is illustrated in the tabular chart and the graph of Figures 6-41 and 6-42. When the load resistance is 5 ohms, thus matching the source resistance, the maximum power of 500 watts is developed in the load.

The efficiency of power transfer (ratio of output power to input power) from the source to the load increases as the load resistance is increased. The efficiency approached 100 per-



R_L	E_T	I	P_L	%
00.0	00.0	20.0	000	00.0
02.5	33.3	13.3	445	33.3
05.0	50.0	10.0	500	50.0
07.5	60.0	08.0	480	60.0
10.0	66.7	06.7	444	66.7
20.0	80.0	04.0	320	80.0
30.0	85.8	02.9	245	85.8
40.0	88.8	02.2	197	88.8
50.0	91.0	01.8	165	91.0
60.0	92.4	01.5	142	92.4

Figure 6-41 - Power transfer and circuit efficiency.

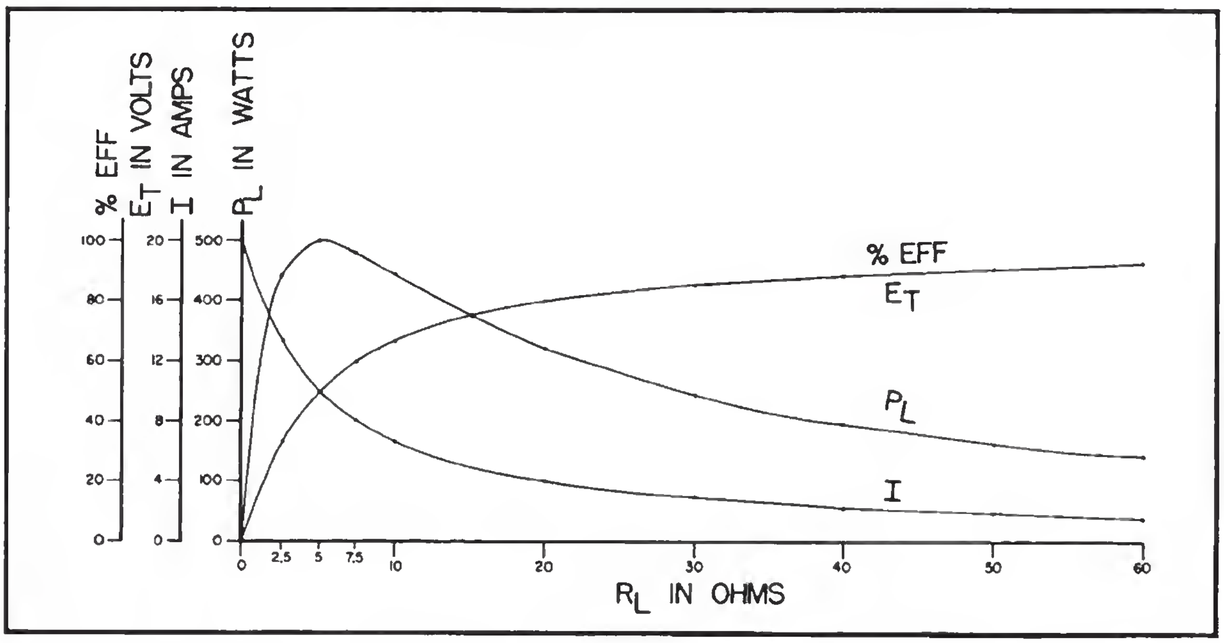


Figure 6-42 - Graph of circuit efficiency.

cent as the load resistance approaches a relatively large value compared with that of the source, since less power is lost in the source. The efficiency of power transfer is only 50 percent at the maximum power transfer resistance of 5 ohms and approaches zero efficiency at relatively low values of load resistance compared with that of the source.

Thus, the problem of high efficiency and maximum power transfer is resolved as a compromise somewhere between the low efficiency of maximum power transfer and the high efficiency of the high-resistance load. Where the amounts of power involved are large and the efficiency is important, the load resistance is made large relative to the source resistance so that the losses are kept small. In this case the efficiency will be high. Where the problem of matching a source to a load is of paramount importance, as in communications circuits, a strong signal may be more important than a high percentage of efficiency. In such cases, the efficiency of transmission will be only about 50 percent. However, the power of transmission will be the maximum of which the source is capable of supplying.

While this chapter has dealt with basic concepts of series circuits, the principles presented are of lasting importance. Once equipped with a firm understanding of series circuits, the reader holds the key to an understanding of the parallel circuits to be presented next.

EXERCISE 6

1. What is a circuit?
2. What is an electrical load?
3. Why may the connecting wires be neglected in most calculations involving simple circuits?
4. Why are schematic diagrams valuable?
5. What is the purpose of a switch?
6. What is meant when a circuit is said to be energized?
7. What is the purpose of a fuse?
8. How are fuses rated?
9. What precaution should always be observed when replacing a blown fuse?
10. What is indicated if a circuit consistantly blows fuses?
11. What relationship always exists between voltage rises and voltage drops in a circuit?
12. State Ohm's Law.
13. What is the voltage required to send a current of 12 amps through a resistance of 60 ohms?
14. A lamp has a resistance of 150 ohms. An E.M.F. of 120 volts is applied; find the current in the line and the voltage across the lamp.
15. What is a volt-ampere characteristic curve?
16. Why is a fixed resistor called a linear device?
17. A 120 watt lamp is operated at 120 volts. What is the value of current flow through the lamp?
18. What is the resistance of the lamp filament in Question 17?
19. What is the maximum voltage that may be applied to a resistor rated at 1000 ohms and 10 watts?
20. Show how a voltmeter and an ammeter can be connected into a circuit to measure the power dissipated by a resistor.
21. What is a series circuit?
22. Six Christmas tree lights, each having thirty ohms resistance are connected across the 120 volt line, what is the current through the first lamp? The third lamp?
23. Three resistors are connected in series, $R_1 = 20\,\Omega$, $R_2 = 5\,\Omega$, $R_3 = 5\,\Omega$. What is the total resistance?
24. A circuit contains four series resistors, R_1 = 25k, R_2 = 100k, R_3 = 250k, R_T = 550k. What is the value of R_4?
25. A circuit contains three resistors in series. $R_1 = 30\,\Omega$, $R_2 = 160\,\Omega$, $R_3 = 40\,\Omega$; if E_1 = 80 volts, what is the value of the applied voltage?
26. Refer to Figure 6-43. What is the value of the applied voltage E_{bb1}?

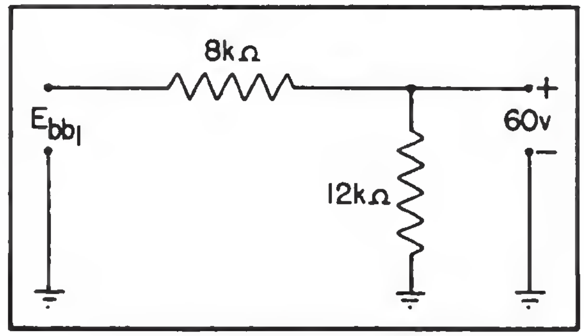


Figure 6-43.

27. Refer to Figure 6-44. Find the value of R_2.

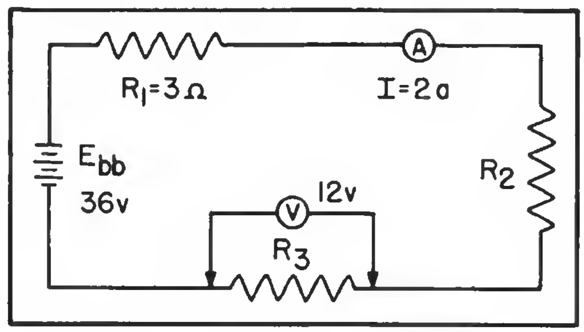


Figure 6-44.

28. Refer to Figure 6-45. Find the voltage drop across R_2.

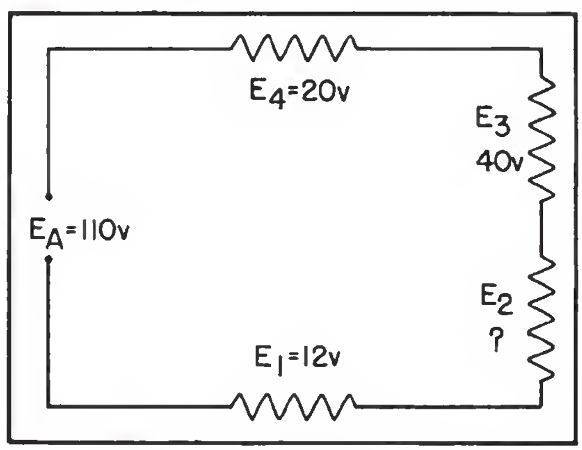


Figure 6-45.

29. The total power consumed in a three resistor series circuit is 100 watts. What is the power dissipated by R_1 if R_3 dissipates 30 watts and the value of R_1 and R_2 are equal?

30. Refer to Figure 6-46. Find E_2, E_3, and E_{bb1}.

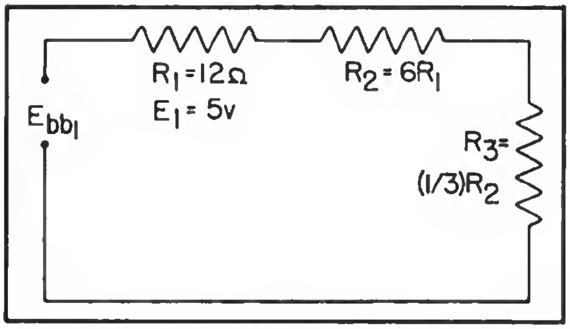


Figure 6-46.

31. Refer to Figure 6-47. Find the voltage present between point A and point B.

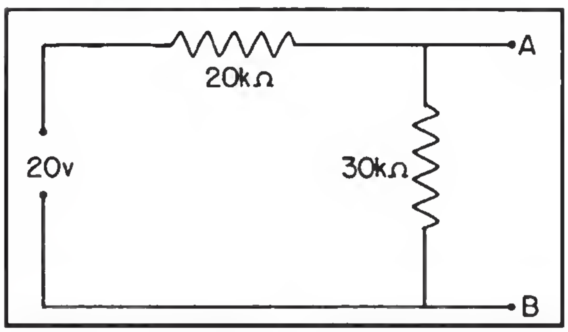


Figure 6-47.

32. In Figure 6-48, find R_T, E_{bb}, and I.

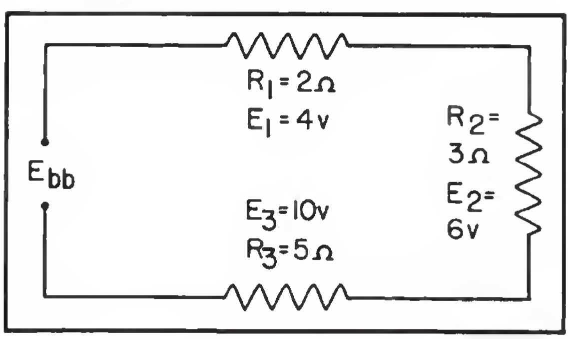


Figure 6-48.

33. In Figure 6-49, what is the voltage at point D in respect to ground?

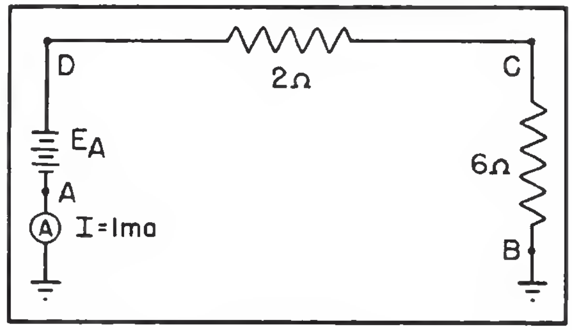


Figure 6-49.

34. Six resistors are connected in series, (Figure 6-50). R_1 = R_2 and R_5 = R_6; R_1 = 30 Ω, R_3 = 40Ω, R_4 = 50Ω, and R_5 = 100Ω. The current through the circuit is 5 amps.

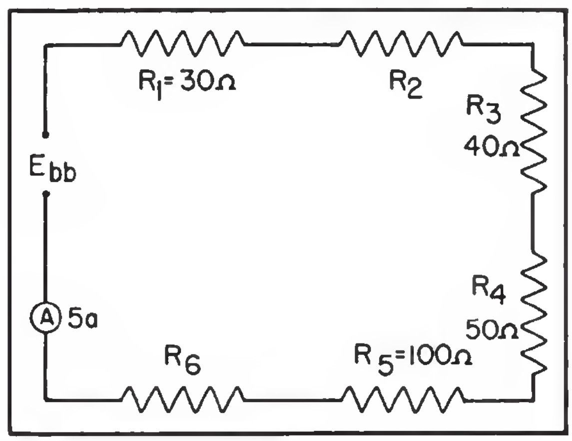


Figure 6-50.

What is the battery voltage?
What is the voltage across each resistor?
What is the power expended in each resistor?
What is the total power?

CHAPTER 7

PARALLEL DC CIRCUITS AND NETWORK ANALYSIS

An adequate understanding of modern electronic equipment requires a progressive development in the study of typical electronic circuits. In stepping-stone fashion, the discussion of series dc circuits will now be followed by a consideration of the characteristics of parallel dc circuits. It will be shown how the principles applied to series circuits can be used to determine the reactions of such quantities as voltage, current, and resistance in parallel and series-parallel circuits.

Along with the progressive introduction of electrical theories and circuit characteristics comes a corresponding progression in the use of mathematical equations and problem solving methods. A basic knowledge of powers of ten, fractions, fractional equations, and the use of simultaneous equations is required for the comprehension of material presented in this chapter. These subjects are discussed in Volume 8.

PARALLEL CIRCUIT CHARACTERISTICS

7-1. Parallel Circuit Defined

A PARALLEL CIRCUIT is defined as one having more than one current path connected to a common voltage source. Parallel circuits, therefore, must contain two or more load resistances which are not connected in series. An example of a basic parallel circuit is shown in Figure 7-1.

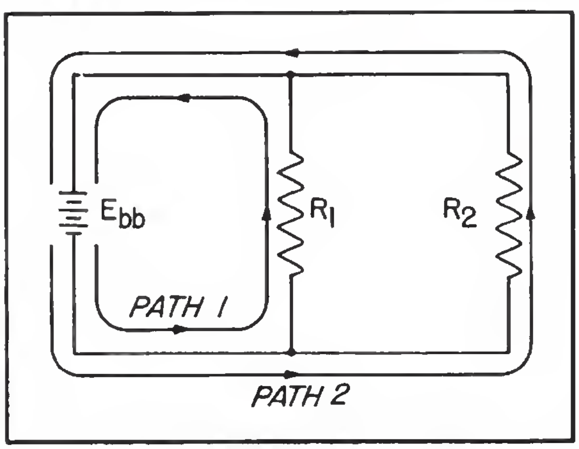


Figure 7-1 - Example of a basic parallel circuit.

Commencing at the voltage source (E_{bb}) and tracing counter-clockwise around the circuit, two complete and separate paths can be identified in which current can flow. One path is traced from the source, through resistance R_1 and back to the source; the other, from the source through resistance R_2 and back to the source.

7-2. Voltage

You have seen that the source voltage in a series circuit divides proportionately across each resistor in the circuit. IN A PARALLEL CIRCUIT (Figure 7-1) THE SAME VOLTAGE IS PRESENT ACROSS ALL THE RESISTORS OF A PARALLEL GROUP. This voltage is equal to the applied voltage (E_{bb}). The foregoing statement can be expressed in equation form as:

$$E_{bb} = E_{R1} = E_{R2} = E_{Rn} \qquad (7\text{-}1)$$

Voltage measurements taken across the resistors of a parallel circuit, as illustrated by Figure 7-2, verify the above equation. Each voltmeter indicates the same amount of voltage. Notice that the voltage across each resistor is the same as the applied voltage.

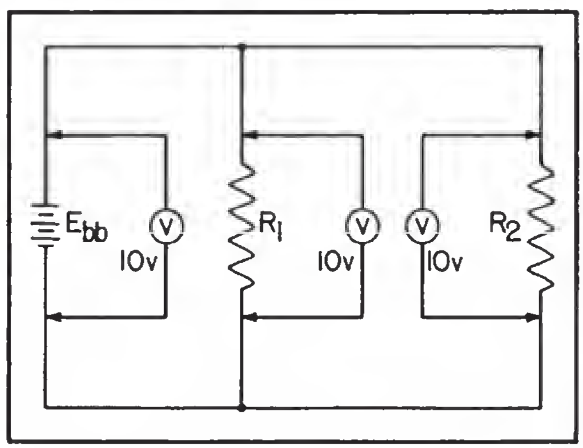


Figure 7-2 - Voltage comparison in a parallel circuit.

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Example. Assume that the current through a resistor of a parallel circuit is known to be 4.5 ma and the value of the resistor is 30,000 ohms. Determine the potential across the resistor. The circuit is shown in Figure 7-3.

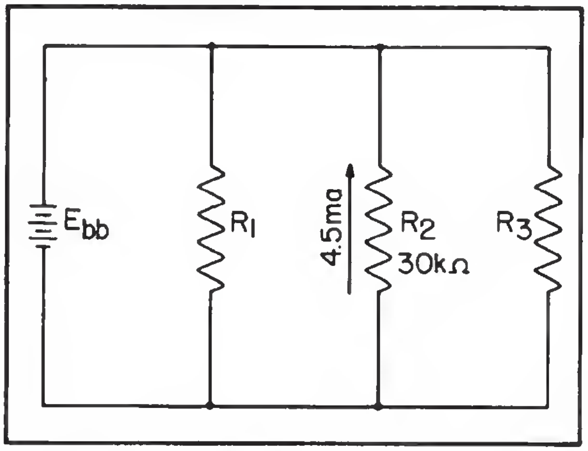

Figure 7-3 - Example problem parallel circuit.

Given: $R_2 = 30K$

$I_{R2} = 4.5ma$

Find: $E_{R2} = ?$

$E_{bb} = ?$

Solution: Select proper equation.

$$E = IR \qquad (6\text{-}2)$$

Substitute known values:

$$E_{R2} = I_{R2} \times R_2$$

$$E_{R2} = 4.5 \text{ ma} \times 30,000 \text{ ohms}$$

Express in powers of ten:

$$E_{R2} = (4.5 \times 10^{-3}) \times (30 \times 10^{3})$$

$$E_{R2} = 4.5 \times 30$$

Resultant: $E_{R2} = 135v$

Therefore: $E_{bb} = 135v$

Having determined the voltage across one resistor (R_2) in a parallel circuit, the value of the source voltage (E_{bb}) and the potentials across any other resistors that may be connected in parallel with it are known (equation 7-1).

Q1. In series circuits the sum of the voltage drops is equal to the source voltage. Why is this not true for the parallel circuit?

7-3. Current Division

"The current in a circuit.......is inversely proportional to the circuit resistance." This fact, obtained from Ohm's law, establishes the relationship upon which the following discussion is developed.

A single current flows in a series circuit. Its value is determined in part by the total resistance of the circuit. However, the source current in a parallel circuit divides among the available paths in relation to the value of the resistors in the circuit. Ohm's law remains unchanged. For a given voltage, current varies inversely with resistance.

The behavior of current in parallel circuits will be shown by a series of illustrations using example circuits with different values of resistance for a given value of applied voltage.

Part (A) of Figure 7-4 shows a basic series circuit. Here the total current must pass through the single resistor. The amount of current is determined as:

$$I_t = \frac{E_{bb}}{R_1} = \frac{50}{10} = 5a$$

Part (B) of Figure 7-4 shows the same resistor (R_1) with a second resistor (R_2) of equal value connected in parallel across the voltage source. Applying the proper equation from Ohm's law, the current flow through each resistor is seen to be the same as through the single resistor in part (A). These individual currents are determined as follows:

$$I_{R1} = \frac{E_{bb}}{R_1} = \frac{50}{10} = 5a$$

$$I_{R2} = \frac{E_{bb}}{R_2} = \frac{50}{10} = 5a$$

However, it is apparent that if five amperes of current flows through each of the two resistors, there must be a TOTAL CURRENT of 10 amperes drawn from the source. The distribution of current in the simple parallel circuit shown in Figure 7-4B is as follows:

The total current of 10 amperes leaves the negative terminal of the battery and flows to point a. Since point a is a connecting point for the two resistors it is called a JUNCTION. At junction a the total current divides into two smaller currents of 5 amperes each. These two currents flow through their respective re-

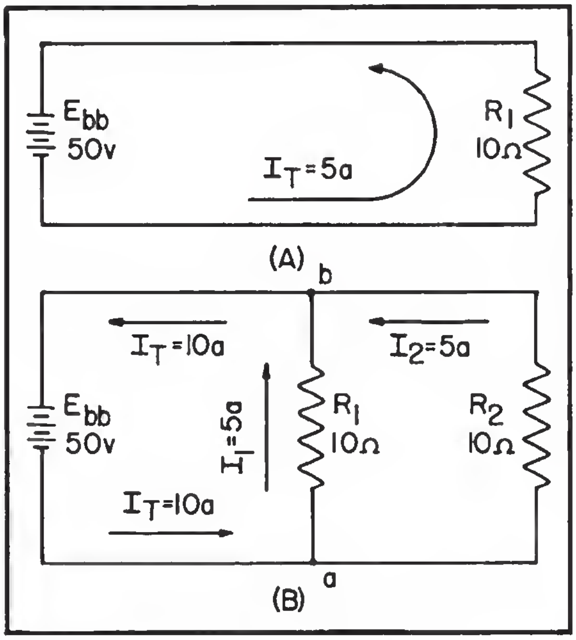

Figure 7-4 - Analysis of current in parallel circuit.

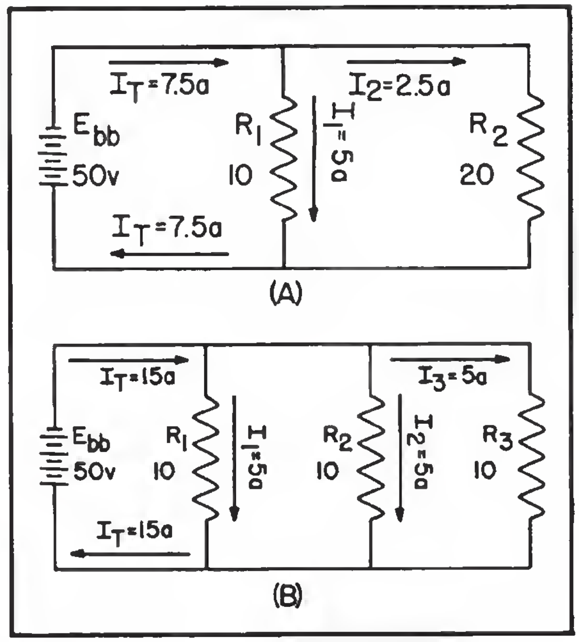

Figure 7-5 - Current behavior in parallel circuits.

sistors and rejoin at junction b. The total current then flows from junction b back to the positive terminal of the source. Thus, the source supplies a total current of 10 amperes and each of the two equal resistors carries one-half the total current.

Each individual current path in the circuit of Figure 7-4B is referred to as a BRANCH. Each branch will carry a current that is a portion of the total current. Two or more branches form a NETWORK.

From the foregoing observations, the characteristics of current in a parallel circuit can be expressed in terms of the following general equation:

$$I_t = I_1 + I_2 + \cdots I_n \qquad (7\text{-}2)$$

The analysis of current in parallel circuits is continued with the use of the following example circuits.

Compare part (A) of Figure 7-5 above with part (B) of the preceding example circuit in Figure 7-4. Notice that doubling the value of the second branch resistor (R_2) has no effect on the current in the first branch (I_{R1}), but does reduce its own branch current (I_{R2}) to one-half its original value. The total circuit current drops to a value equal to the sum of the branch currents. These facts are verified as follows:

$$I_1 = \frac{E_{bb}}{R_1} = \frac{50}{10} = 5a$$

$$I_2 = \frac{E_{bb}}{R_2} = \frac{50}{20} = 2.5a$$

$$I_t = I_1 + I_2$$

$$I_t = 5 + 2.5 = 7.5a$$

Now compare the two circuits of Figure 7-5. Notice that the sum of the ohmic values of the resistors in both circuits is equal and that the applied voltage is the same value. However, the total current in part (B) is twice the amount in part (A). It is apparent, therefore, that the manner in which resistors are connected in a circuit as well as their actual ohmic value, affects the total current flow. This phenomenon will be illustrated in more detail in the discussion of resistance. The amount of current flow in the branch circuits and the total current in the circuit, part (B), Figure 7-5, is determined as follows:

$$I_1 = \frac{E_{bb}}{R_1} = \frac{50}{10} = 5a$$

$$I_2 = \frac{E_{bb}}{R_2} = \frac{50}{10} = 5a$$

A1. In a parallel circuit each of the branches is connected across the source and the voltage drop across each branch is equal to the applied voltage.

$$I_3 = \frac{E_{bb}}{R_3} = \frac{50}{10} = 5a$$

$$I_t = I_1 + I_2 + I_3 \qquad (7\text{-}2)$$

$$I_t = \frac{E_{bb}}{R_1} + \frac{E_{bb}}{R_2} + \frac{E_{bb}}{R_3}$$

$$I_t = \frac{50}{10} + \frac{50}{10} + \frac{50}{10} = 15a$$

The division of current in a parallel network follows a definite pattern. This pattern is described by KIRCHHOFF'S CURRENT LAW (his First Law) which is stated as follows:

LAW 1. The algebraic sum of the currents entering and leaving any junction of conductors is equal to zero.

This law can be stated mathematically as:

$$I_a + I_b + \cdots\cdots + I_n = 0 \qquad (7\text{-}3)$$

where: I_a, I_b, etc., are the currents entering and leaving the junction. Currents ENTERING the junction are assumed to be POSITIVE and currents LEAVING the junction are considered NEGATIVE. When solving a problem using equation (7-3), the currents must be placed into the equation WITH THE PROPER POLARITY SIGNS ATTACHED.

Example. Solve for the value of I_3 in Figure 7-6.

Solution: First the currents are given proper signs.

$$I_1 = +10a$$

$$I_2 = -3a$$

$$I_3 = ?a$$

$$I_4 = -5a$$

These currents are placed into equation (7-3) with the proper signs as follows:

Basic equation: $I_a + I_b + \cdots\cdots I_n = 0$ (7-3)

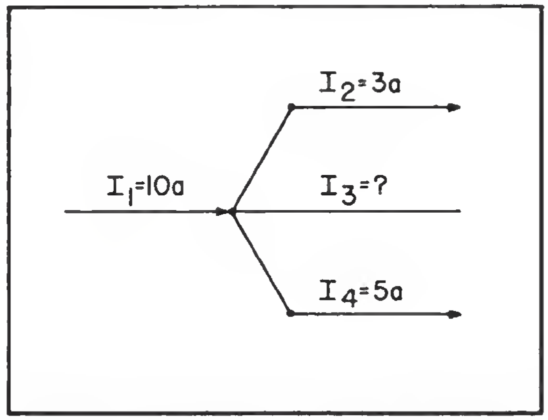

Figure 7-6 - Circuit for example problem.

substitution:

$$I_1 + I_2 + I_3 + I_4 = 0$$

$$(+10) + (-3) + (I_3) + (-5) = 0$$

combining like terms:

$$I_3 + 2 = 0$$

$$I_3 = -2a$$

Thus, I_3 has a value of 2 amperes, and the negative sign shows it to be a current LEAVING the junction.

Example. Using Figure 7-7, solve for the magnitude and direction of I_3:

Solution: $I_a + I_b + \cdots\cdots + I_n = 0$ (7-3)

$$I_1 + I_2 + I_3 + I_4 = 0$$

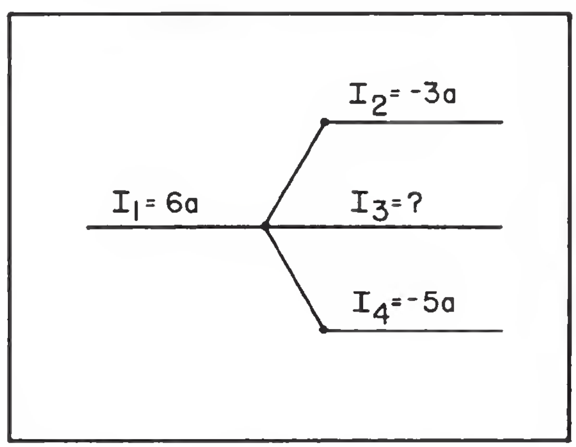

Figure 7-7 - Circuit for example problem.

$$(+6a) + (-3a) + (I_3) + (-5a) = 0$$

$$I_3 - 2a = 0$$

$$I_3 = 2a$$

Thus, I_3 is 2 amperes and its positive sign shows it to be a current entering the junction.

Q2. If a branch resistance of a parallel network becomes open, how will this affect the total current? How will this affect the potential difference across other branches of the circuit?

Q3. Does the current divide equally between the branches of a parallel network? Explain.

7-4. Parallel Resistances

The preceding discussion of current introduced certain principles involving the characteristics and effects of resistance in parallel circuits. A detailed explanation of the characteristics of parallel resistances will be considered in this section. The explanation will commence with a simple parallel circuit. Various methods used to determine the total resistance in parallel circuits will be described.

In the example diagram, Figure 7-8, two cylinders of conductive material having a resistance value of ten ohms each are connected across a five volt battery. A complete circuit consisting of two parallel paths is formed and current will flow as shown.

Computing the individual currents shows that there is one half an ampere of current flowing through each resistance. Accordingly, the total current flowing from the battery to the junction of the resistors, and returning from the resistors to the battery, is equal to one ampere.

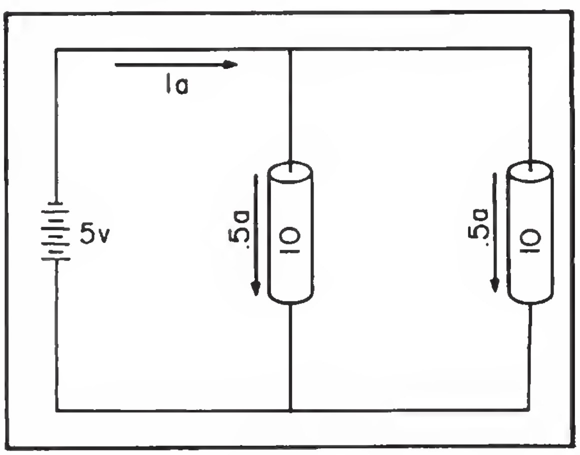

Figure 7-8 - Two equal resistors connected in parallel.

The total resistance of the circuit can be determined by substituting total values of voltage and current into the following equation. This equation is derived from Ohm's law.

$$R_t = \frac{E_t}{I_t}$$

$$R_t = \frac{5}{1} = 5 \text{ ohms}$$

This computation shows the total resistance to be 5 ohms, one half the value of either of the two resistors.

Since the total resistance of this parallel circuit is smaller than either of the two resistors, the term "total resistance" does not mean the sum of the individual resistor values. The total resistance of resistors in parallel is also referred to as EQUIVALENT RESISTANCE. In many texts the terms total resistance and equivalent resistances are used interchangeably.

There are several methods used to determine the equivalent resistance of parallel circuits. The most appropriate method for a particular circuit depends on the number and value of the resistors. For the circuit described above, the following simple equation is used:

$$R_{eq} = \frac{R}{N} \qquad (7\text{-}4)$$

where: R_{eq} = equivalent parallel resistance

R = ohmic value of one resistor

N = number of resistors

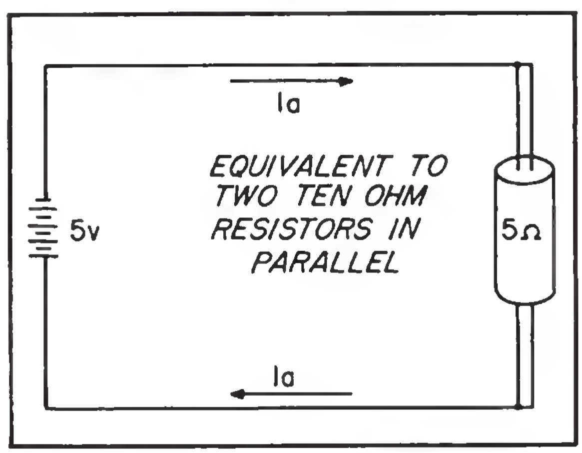

Figure 7-9 - Equivalent parallel circuit.

A2. The total current of the circuit will decrease. The potential applied to the parallel branches will remain the same.

A3. The current divides in proportion to the value of the resistance of the branch. Unless the resistors are equal the current will not divide equally.

This equation is valid for any number of EQUAL VALUE parallel resistors.

An understanding of why the equivalent resistance of two parallel resistors is smaller than the resistance of either of the two resistors can be gained by an examination of Figure 7-8. The two ten ohm cylinders have fixed equal volumes. If the cylinders were combined into one cylinder as shown in Figure 7-9, the volume would double. If the same length is retained and the volume is doubled, the cross-sectional area will double. When the cross-sectional area of a material is increased the resistance is decreased proportionately.

Since, in this case, the cross-sectional area is two times the original area, the resistance is one-half the former value. Therefore, when two equal value resistors are connected in parallel they present a total resistance equivalent to a single resistor of one-half the value of either of the original resistors.

Example. Four forty-ohm resistors are connected in parallel. What is their equivalent resistance?

Solution: $R_{eq} = \frac{R}{N} = \frac{40}{4} = 10$ ohms

Circuits containing parallel resistance of unequal value will now be considered. Refer to example circuit in Figure 7-10.

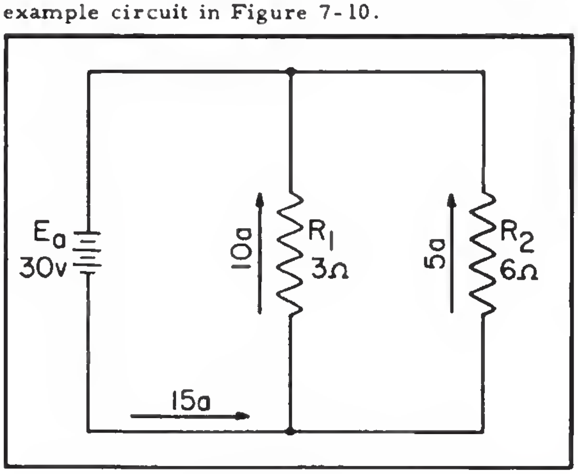

Figure 7-10 - Example circuit with unequal parallel resistors.

Given: $R_1 = 3\Omega$, $R_2 = 6\Omega$, $E_a = 30v$

Known: $I_1 = 10a$, $I_2 = 5a$, $I_t = 15a$

Determine: $R_{eq} = ?$

Solution: $R_{eq} = \frac{E_a}{I_t}$

$$R_{eq} = \frac{30}{15} = 2 \text{ ohms}$$

Notice that the equivalent resistance of two ohms is less than the value of either branch resistor. IN PARALLEL CIRCUITS THE EQUIVALENT RESISTANCE WILL ALWAYS BE SMALLER THAN THE RESISTANCE OF ANY BRANCH.

7-5. Reciprocal Method

Many circuits are encountered in which resistors of unequal value are connected in parallel. It is therefore desirable to develop a formula which can be used to compute the equivalent resistance of two or more unequal parallel resistors. This equation can be derived as follows.

Given: $I_t = I_1 + I_2 + \cdots I_n$ (7-2)

Substituting $\frac{E}{R}$ for I gives:

$$\frac{E_t}{R_t} = \frac{E_1}{R_1} + \frac{E_2}{R_2} + \cdots\cdots \frac{E_n}{R_n}$$

Since in a parallel circuit $E_t = E_1 = E_2 = E_n$

$$\frac{E}{R_t} = \frac{E}{R_1} + \frac{E}{R_2} + \cdots\cdots\cdot \frac{E}{R_n}$$

Dividing both sides by E:

$$\frac{E}{ER_t} = \frac{E}{ER_1} + \frac{E}{ER_2} + \cdots\cdots \frac{E}{ER_n}$$

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots\cdots \frac{1}{R_n}$$

Taking the reciprocal of both sides:

$$\frac{1}{\frac{1}{R_t}} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \cdots\cdot \frac{1}{R_n}}$$

Simplifying:

$$R_t = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \cdots\cdots \frac{1}{R_n}} \qquad (7\text{-}5)$$

This formula is called "the reciprocal of the sum of the reciprocals" and is the one normally used to solve for the equivalent resistance of a number of parallel resistors.

Example. Given three parallel resistors of 20 ohms, 30 ohms, and 40 ohms, find the equivalent resistance using the reciprocal equation. (See Figure 7-11.)

Solution:

Select the proper equation: $R_{eq} = \dfrac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$

Substitute: $R_{eq} = \dfrac{1}{\frac{1}{20} + \frac{1}{30} + \frac{1}{40}}$

find LCD: $R_{eq} = \dfrac{1}{\frac{6}{120} + \frac{4}{120} + \frac{3}{120}} = \dfrac{1}{\frac{13}{120}}$

invert: $R_{eq} = \dfrac{120}{13} = 9.23$ ohms

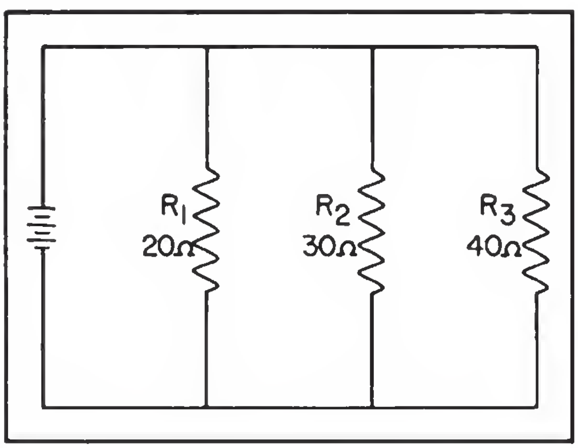

Figure 7-11 - Example parallel circuit with unequal branch resistors.

Some parallel circuit problems can be solved more conveniently by considering the ease with which current can flow. The degree to which a circuit permits or conducts current is called the CONDUCTANCE (G) of the circuit. The unit of conductance is the MHO, which is ohms spelled backwards. The conductance of a circuit is the reciprocal of the resistance. The conductance can therefore be found using the following formula:

$$G = \frac{1}{R} \qquad (5\text{-}5)$$

also: $$R = \frac{1}{G} \qquad (5\text{-}4)$$

In a parallel circuit the total conductance is equal to the sum of the individual branch conductances. As an equation:

$$G_t = G_1 + G_2 + \cdots\cdots G_n \qquad (7\text{-}6)$$

Example. Determine the equivalent (total) resistance of the circuit shown in the preceding example (Figure 7-11) using the conductance method.

Solution: $G_1 = \dfrac{1}{R_1} = \dfrac{1}{20} = 0.050$ mho

$G_2 = \dfrac{1}{R_2} = \dfrac{1}{30} = 0.033$ mho

$G_3 = \dfrac{1}{R_3} = \dfrac{1}{40} = 0.025$ mho

$$G_t = G_1 + G_2 + G_3 \qquad (7\text{-}6)$$

$G_t = 0.050 + 0.033 + 0.025 = 0.108$ mho

Since: $$R_t = \frac{1}{G_t} \qquad (7\text{-}7)$$

$R_t = \dfrac{1}{0.108} = 9.25$ ohms

The value of equivalent resistance determined by the conductance method is almost identical to the value determined by the reciprocal of the sum of the reciprocals methods.

7-6. Product Over the Sum

A convenient formula for finding the equivalent resistance of TWO parallel resistors can be derived from equation (7-5) as shown below:

$$R_t = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}} \qquad (7\text{-}5)$$

Finding the LCD:

$$R_t = \frac{1}{\frac{R_2 + R_1}{R_1 \times R_2}}$$

Taking the reciprocal:

$$R_t = \frac{R_1 \times R_2}{R_1 + R_2}$$

This equation, called the product over the sum formula, is used so frequently it should be committed to memory.

Example. What is the equivalent resistance of a 20 ohm and a 30 ohm resistor connected in parallel?

Given: $R_1 = 20$

$R_2 = 30$

Find: $R_{eq} = ?$

Solution:
$$R_t = \frac{R_1 \times R_2}{R_1 + R_2} \qquad (7\text{-}8)$$

$$R_t = \frac{20 \times 30}{20 + 30}$$

$$R_t = 12 \text{ ohms}$$

Q4. Doubling the cross-sectional area of a conductor connected across a voltage source would have what effect on current?

Q5. If two equal value resistors are connected in parallel, which of the following will be their equivalent resistance?

(a) one-fourth the value of one
(b) one-half the value of one
(c) equal the value of one
(d) equal the sum of both

7-7. Parallel Circuit Reduction

In the study of electricity, it is often necessary to resolve a complex circuit into a simpler form. Any complex circuit consisting of resistances, can be reduced to a basic equivalent circuit containing the source and total resistance. This process is called reduction to an EQUIVALENT CIRCUIT. An example of circuit reduction is shown in Figure 7-12.

The circuit shown in (A) of Figure 7-12 is reduced to the simple circuit shown in (B) of Figure 7-12.

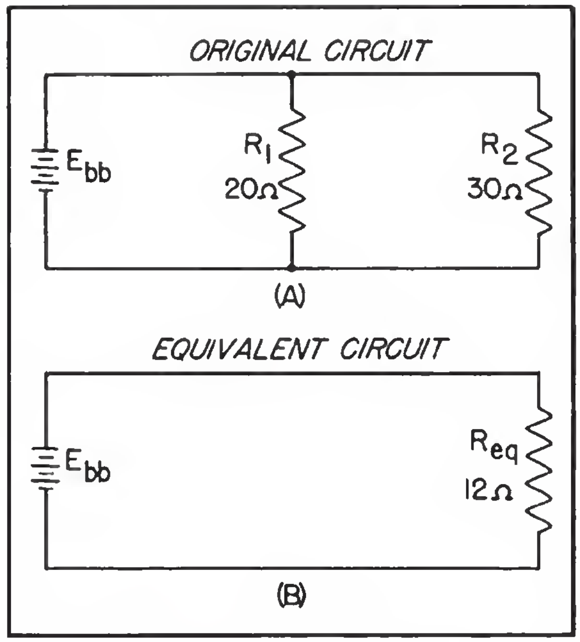

Figure 7-12 - Parallel circuit with equivalent circuit.

7-8. Computing Total Power

Power computations in a parallel circuit are essentially the same as those used for the series circuit. Since power dissipation in resistors consists of a heat loss, power dissipations are additive regardless of how the resistors are connected in the circuit. The total power dissipated is equal to the sum of the powers dissipated by the individual resistors. Like the series circuit, the total power consumed by the parallel circuit is:

$$P_t = P_1 + P_2 + \cdots P_n \qquad (6\text{-}12)$$

Example. Find the total power consumed by the circuit in Figure 7-13.

Solution:
$$P_{R1} = E_{bb} \times I_{R1}$$

$$P_{R1} = 50 \times 5$$

$$P_{R1} = 250W$$

$$P_{R2} = E_{bb} \times I_{R2}$$

$$P_{R2} = 50 \times 2$$

$$P_{R2} = 100W$$

$$P_{R3} = E_{bb} \times I_{R3}$$

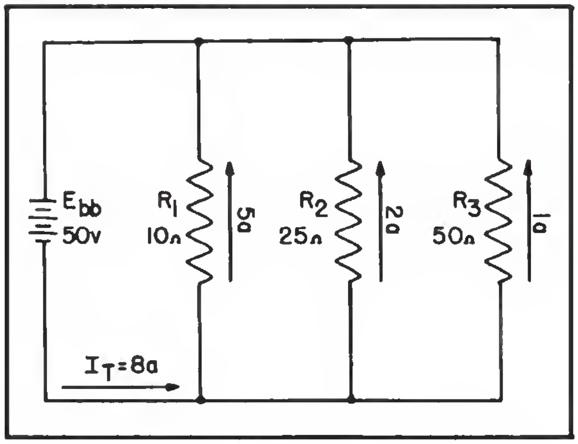

Figure 7-13 - Example parallel circuit.

$$P_{R3} = 50 \times 1$$

$$P_{R3} = 50W$$

$$P_t = P_1 + P_2 + P_3$$

$$P_t = 250 + 100 + 50$$

$$P_t = 400W$$

Note that the power dissipated in the branch circuits is determined in the same manner as the power dissipated by individual resistors in a series circuit. The total power (P_t) is then obtained by summing up the powers dissipated in the branch resistors using equation (6-12).

Since, in the example shown in Figure 7-13, the total current is known, the total power could be determined by the following method:

$$P_t = E_{bb} \times I_t$$

$$P_t = 50v \times 8a$$

$$P_t = 400W$$

RULES FOR PARALLEL DC CIRCUITS

1. The same voltage exists across each branch of a parallel circuit and is equal to the source voltage.

2. The current through a branch of a parallel network is inversely proportional to the amount of resistance of the branch.

3. The total current of a parallel circuit is equal to the sum of the currents of the individual branches of the circuit.

4. The total resistance of a parallel circuit is equal to the reciprocal of the sum of the reciprocals of the individual resistances of the circuit.

5. The total power consumed in a parallel circuit is equal to the sum of the power consumptions of the individual resistances.

SERIES PARALLEL COMBINATIONS

In the preceding discussions, series and parallel dc circuits have been considered separately. However, the electronics technician will seldom encounter a circuit that consists solely of either type of circuit. Most circuits consist of both series and parallel elements. A circuit of this type will be referred to as a COMBINATION CIRCUIT. The solution of a combination circuit is simply a matter of application of the laws and rules discussed prior to this point.

7-9. Solving a Combination Circuit

To demonstrate the method of solution used for combination circuits, the network shown in Figure 7-14 will be completely solved. Close examination of the circuit shows that the only quantity that can be computed with the given information is the equivalent resistance of R_2 and R_3. However, once this quantity is known, it can be added to R_1 to obtain the total resistance of the circuit. Thus:

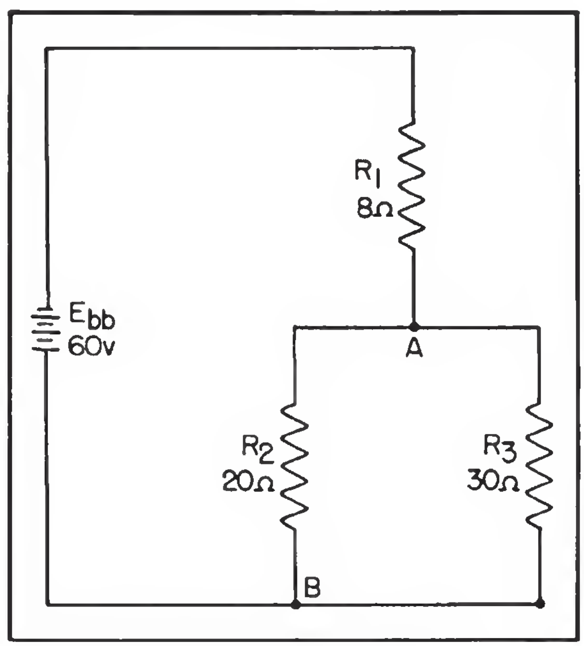

Figure 7-14 - Example combination circuit.

A4. The current will be double its former value.

A5. Answer (b), one-half the value of one.

$$R_t = R_1 + R_{eq}$$

or:

$$R_t = R_1 + \frac{R_2R_3}{R_2 + R_3}$$

$$R_t = 8 + \frac{20 \times 30}{20 + 30}$$

$$R_t = 8 + 12$$

$$R_t = 20 \text{ ohms}$$

Once the total resistance is known the total current can be found by Ohm's law.

$$I_t = \frac{E_t}{R_t}$$

$$I_t = \frac{60}{20}$$

$$I_t = 3 \text{ amps}$$

Again examining Figure 7-14, the total current of 3 amps is seen to flow through R_1, an 8 ohm resistor. The voltage across this resistor is thus:

$$E_{R1} = I_tR_1$$

$$E_{R1} = 3 \times 8$$

$$E_{R1} = 24 \text{ volts}$$

Since 60 volts are applied to the circuit and 24 of these 60 volts are dropped across R_1, the remaining 36 volts must be dropped across the two parallel resistors R_2 and R_3 (Kirchhoff's voltage law). The currents through R_2 and R_3 are:

$$I_{R2} = \frac{E_{R2}}{R_2}$$

$$I_{R2} = \frac{36}{20}$$

$$I_{R2} = 1.8 \text{ amps}$$

and:

$$I_{R3} = \frac{E_{R3}}{R_3}$$

$$I_{R3} = \frac{36}{30}$$

$$I_{R3} = 1.2 \text{ amps}$$

Having computed all the currents and voltages of Figure 7-14, a complete description of the operation of the circuit can be made. The total current of 3 amps leaves the negative terminal of the battery and flows through the 8 ohm resistor. In so doing, a voltage drop of 24 volts occurs across this resistor. At point A this 3 ampere current divides into two currents. Of the total, 1.8 amps flow through the 20 ohm resistor. This current produces a 36 volt drop across the 20 ohm resistor. The remaining current of 1.2 amps flows from point A, down through the 30 ohm resistor to point B. This current produces a voltage drop of 36 volts across the 30 ohm resistor. Notice that the voltage drops across the 20 and 30 ohms resistors are the same. The two branch currents of 1.8 and 1.2 amps combine at junction B and the total current of 3 amps flows back to the source. The action of the circuit has been completely described with the exception of the power dissipations which, if necessary, could be computed using methods previously shown.

It should be pointed out that the combination circuit is not difficult to solve. The key to its solution lies in knowing the order in which the steps of the solution must be accomplished.

Q6. Why is it advisable to draw an equivalent circuit?

Q7. Is the equivalent circuit of a series-parallel combination a series or a parallel circuit?

Q8. Why is the voltage drop across parallel networks of a combination circuit NOT equal to the source voltage?

7-10. Effects of Source Resistance

The parallel circuits discussed up to this point have been explained and solved without considering the internal resistance of the source. Every known source possesses resistance. In a battery the resistance is partially due to the opposition offered to the movement of ions through the electrolyte. A schematic representation of source resistance is shown in Figure 7-15.

The internal resistance of the battery is labeled (R_i) and is always shown schematically

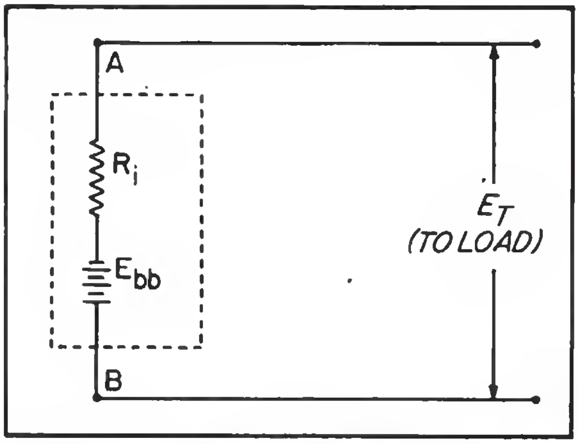

Figure 7-15 - Battery with internal resistance.

connected in series with the source. Under load conditions this internal resistance will have a voltage drop across it and must be considered as part of the external circuit. The voltage at battery terminals A and B will always be less than the generated voltage of the battery since a portion of the generated voltage will be dropped across the internal resistance of the battery.

The presence of internal resistance results in (1) a diminished voltage supplied to the components that comprise the load, (2) a decrease in total current, and (3) an increase in total resistance. The power dissipated by the circuit is also affected. The effect of internal resistance on the circuit is analyzed using the example circuit shown in Figure 7-16.

The circuit shown in Figure 7-16 can no longer be classified as a parallel circuit because there is a series resistance to be considered. The circuit is solved in the following manner.

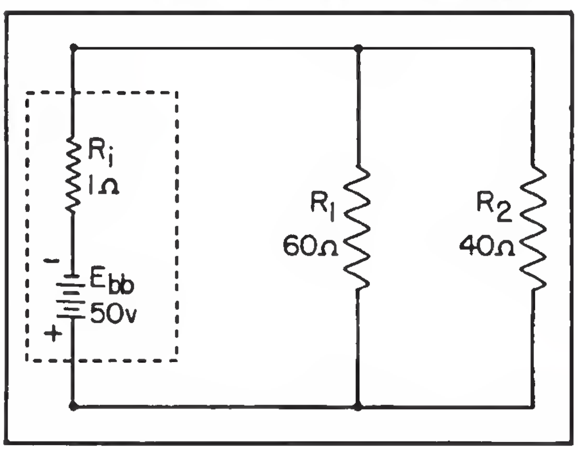

Figure 7-16 - Effect of source resistance on a parallel circuit.

Determine R_{eq} for the parallel network:

$$R_{eq} = \frac{R_1 \times R_2}{R_1 + R_2} = \frac{60 \times 40}{60 + 40} = \frac{2400}{100} = 24 \text{ ohms}$$

Reduce to an equivalent circuit (Figure 7-17)

Compute the total series resistance:

$$R_t = R_1 + R_{eq}$$

$$R_t = 1 + 24 = 25 \text{ ohms}$$

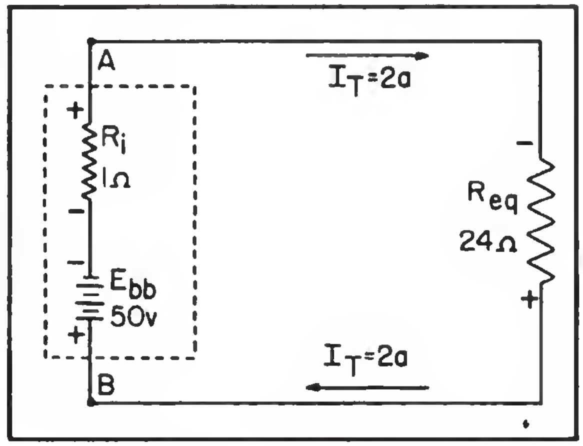

Figure 7-17 - Equivalent circuit.

Compute total current:

$$I_t = \frac{E_{bb}}{R_t} = \frac{50\text{V}}{25} = 2 \text{ amps}$$

Determine voltage drop across R_{eq}:

$$E_{R_{eq}} = I_t \times R_{eq}$$

$$E_{R_{eq}} = 2 \times 24$$

$$E_{R_{eq}} = 48\text{V}$$

Find voltage drop across R_i:

$$E_{R_i} = I_t \times R_i$$

$$E_{R_i} = 2\text{a} \times 1 \text{ ohm}$$

$$E_{R_i} = 2\text{V}$$

A6. In order to visualize the relationship of voltage, current and resistance in a circuit and be better able to select the most appropriate method of solution.

A7. Series circuit.

A8. Because of the voltage drop across the series resistances.

Determine power dissipated by load resistors:

$$P_{R_{eq}} = I_t \times E_{R_{eq}}$$

$$P_{R_{eq}} = 2a \times 48V$$

$$P_{R_{eq}} = 96W$$

Determine power dissipated by source resistance:

$$P_{R_i} = I_t \times E_{R_i}$$

$$P_{R_i} = 2a \times 2V$$

$$P_{R_i} = 4W$$

Determine total power dissipation:

$$P_t = P_{R_{eq}} + P_{R_i}$$

$$P_t = 96W + 4W$$

$$P_t = 100W$$

Circuit efficiency is determined by the following formula:

$$\%\ \text{Eff.} = \frac{P_o}{P_{in}} \times 100 \qquad (7\text{-}9)$$

where: % Eff = percent of efficiency

P_o = power supplied to the load device

P_{in} = power supplied by the source

For the circuit of Figure 7-17 the % Eff. is:

$$\%\ \text{Eff} = \frac{P_o}{P_{in}} \times 100$$

$$\%\ \text{Eff} = \frac{96}{96 + 4} \times 100$$

$$\%\ \text{Eff} = \frac{96W}{100W} \times 100 = 96\%$$

From this efficiency relationship, we may conclude that the source resistance does effect the total power dissipated by the equivalent (load) resistance. The source resistance also affects the transfer of power. As stated in the preceding chapter, maximum transfer of power occurs when the circuit is fifty percent efficient, or when there is an equal amount of voltage dropped across the load and the source resistance.

Q9. What is the relationship between the internal resistance of the source and the voltage applied to the load?

Q10. As the internal resistance increases, what happens to circuit efficiency?

7-11. Open and Short Circuits

In comparing the effects of an open in series and parallel circuits, the major difference to be noted is that an open in a parallel circuit would not necessary disable the entire circuit, i.e., the current flow would not be reduced to zero, unless the open condition existed at some point electrically common to all other parts of the circuit.

A short circuit in a parallel network has an effect similar to a short in a series circuit. In general, the short will cause an increase in current and the possibility of component damage regardless of the type of circuit involved.

Opens and shorts, alike, if occurring in a branch circuit of a parallel network, will result in an overall change in the equivalent resistance. This can cause undesirable effects in other parts of the circuit due to the corresponding change in the total current flow.

7-12. Equipment Protection

To prevent damage to equipment due to a short circuit, a fuse or overload relay is normally placed in the circuit in series with the more sensitive components or in series with the source. The effects of a short circuit occurring in a fused network is shown in Figure 7-18 and is explained as follows:

In Figure 7-18, with the switch in position one (as shown) a value of current flows that does not exceed the rated current capacity of the fuse. If the switch is thrown to position two, the straight wire conductor will be in par-

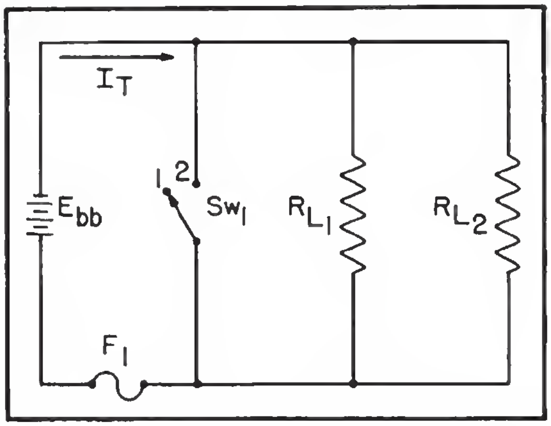

Figure 7-18 - Example of a circuit protected from shorts by a fuse.

allel with the load resistors. The equivalent resistance of the straight wire and the resistors, all connected in parallel, will be less than the resistance of the straight wire. This follows from the fact that the total resistance of a parallel circuit is always less than the smallest resistance in the branch. Since a complete path still exists to permit current flow, and the equivalent resistance is effectively zero, the current will rise rapidly until the current capacity of the fuse is reached. The fuse will then open the circuit causing the current to stop flowing. A short usually causes components to fail in a circuit which is not properly fused, or otherwise protected. The failure may take the form of a burned-out resistor, damaged source, or a fire in the circuit components and wiring.

Q11. If a circuit becomes open, what happens to the circuit current?

Q12. The ohmic value of a short circuit is thought of as having what numeric value?

7-13. Voltage Dividers

In most electronic equipment, both positive and negative voltages of various magnitudes are commonplace. These voltages may be obtained by using a VOLTAGE DIVIDER. A voltage divider is a series resistive circuit tapped so that various voltages can be supplied to different loads from a single source. A voltage divider capable of furnishing positive and negative voltages is shown in Figure 7-19.

The location of the reference point (ground) has been selected to enable the voltage divider to provide both positive and negative voltages. The applied voltage is connected as shown in Figure 7-19 and current flows in the direction

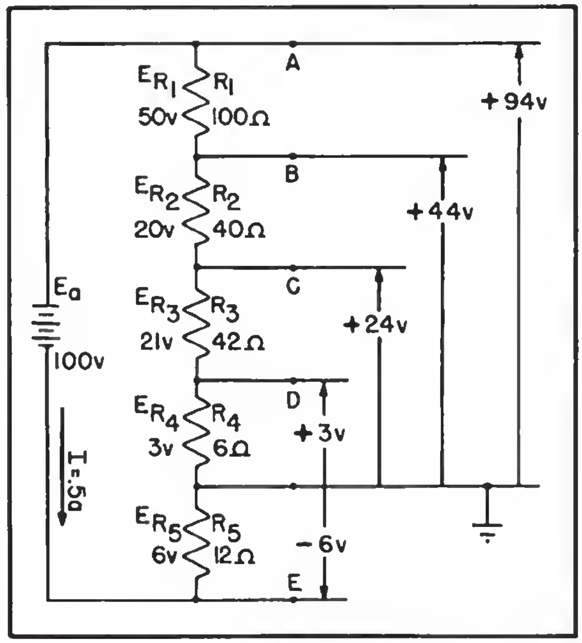

Figure 7-19 - Voltage divider circuit.

indicated. Using ground as a reference, the potential at point (E) is six volts negative. The voltages at points (D), (C), (B), and (A) are respectively three volts positive, twenty-four volts positive, forty-four volts positive and ninety-four volts positive. If the reference point is changed to point (D) there will then be two negative voltages available. One would be the voltage drop across R4 and the other, the voltage drop across R4 and R5. The remainder of the voltage drops will be positive but their magnitudes with respect to ground will be different from the previous example. The total resistance of the voltage divider is two hundred ohms. If a load resistance is placed across any of the resistors, voltage will be supplied to the load resistance and current will be drawn by it. When current is drawn from the divider, the total current flowing in the circuit will increase because the total resistance of the circuit has decreased. If a load device is placed across each of the divider resistors, the circuit will appear as the series-parallel circuit shown in Figure 7-20.

If the total current flowing in the divider circuit is affected by the loads placed on it, then the voltage drops of each divider resistor will also be affected. When a voltage divider is being designed, the maximum current drawn by the loads will determine the value of the resistors that form the voltage divider. Normally, the resistance values chosen for the divider will

A9. As the internal resistance increases, the voltage across the load decreases.

A10. It decreases.

A11. The current flow ceases in the branch containing the open. Other branch currents remain the same.

A12. Zero.

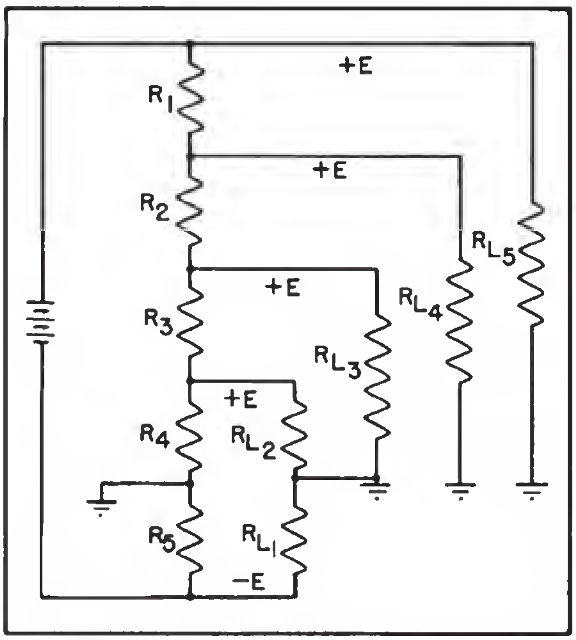

Figure 7-20 - Example voltage divider with multiple load devices.

permit a current equal to ten percent of the total current drawn by the external loads. This current which does not flow through any of the load devices is called BLEEDER CURRENT.

A simple voltage divider with no load applied is shown in Figure 7-21.

The voltage divider illustrated is composed of two resistors of equal value. Therefore, the voltage drop across each resistance will be the same. The total current flowing in the circuit will be:

$$I_t = \frac{Ebb}{R_t} = \frac{100}{5k+5k} = \frac{100}{10k} = 10 \text{ ma}$$

The potential difference between points (A) and (B) is equal to fifty volts. If a resistor is placed between (A) and (B), the voltage drop between these points will be reduced. Figure 7-22

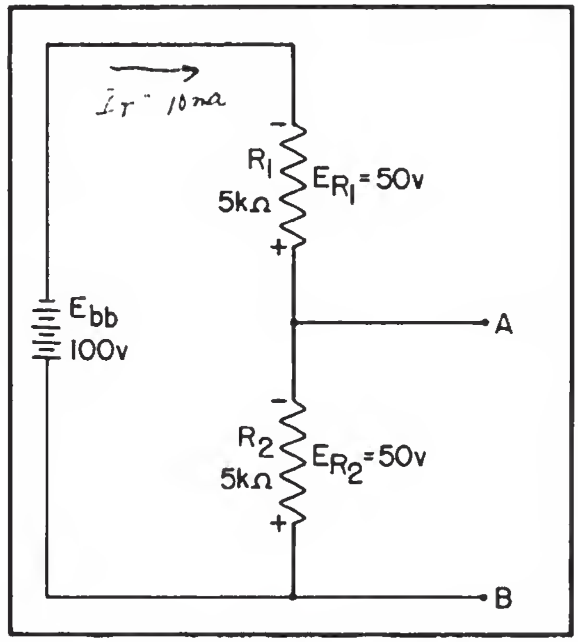

Figure 7-21 - Simple voltage divider with no load applied.

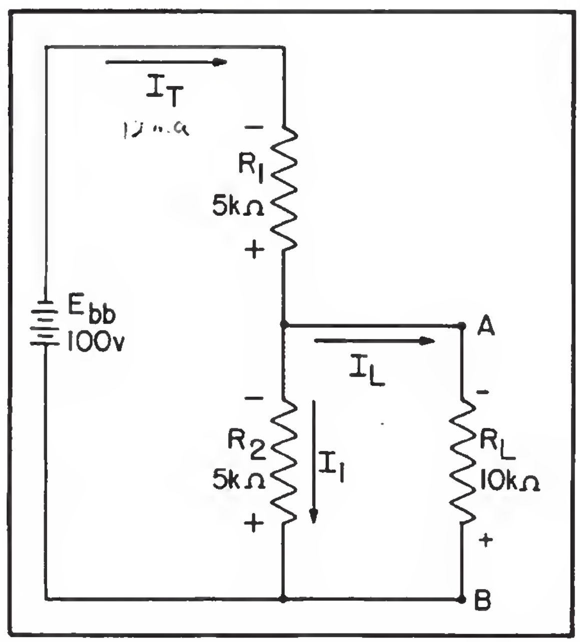

Figure 7-22 - Voltage divider with one section loaded.

shows the same divider circuit with a load resistor connected. The total resistance may be computed:

$$R_t = R_1 + \frac{R_2R_L}{R_2+R_L} = 5k + \frac{5k \times 10k}{5k + 10k}$$

$$R_t = 5 \times 10^3 + \frac{50 \times 10^6}{15 \times 10^3}$$

$$R_t = 5 \times 10^3 + 3.33 \times 10^3$$

$$R_t = 8.33 \times 10^3 = 8.33k \text{ ohms}$$

It can be seen that the total resistance has decreased now that a load has been added. This results in a corresponding increase in current flow. Total current is determined as follows:

$$I_t = \frac{E_{bb}}{R_t} = \frac{100}{8.33 \times 10^3} = 12ma$$

An analysis of the voltage drops shows the following change in the voltage distribution of the circuit.

$$E_{R1} = R_1 \times I_t$$

$$E_{R1} = (5\times10^3)(12\times10^{-3})$$

$$E_{R1} = 60v$$

$$E_{R2} = E_{bb} - E_{R1}$$

$$E_{R2} = 100-60$$

$$E_{R2} = 40v$$

Notice that while the value of the voltage between points (A) and (B) is reduced the voltage drop across R_1 is increased.

The amount of current flow through the load can be found in this manner:

since: $E_{R_L} = E_{R2} = 40v$

then: $I_{R_L} = \frac{E_{RL}}{R_L} = \frac{40}{10\times10^3} = 4ma$

and: $I_{R2} = \frac{E_{R2}}{R_2} = \frac{40}{5\times10^3} = 8ma$

If an additional resistance is added the voltages and currents will differ considerably. Figure 7-23 shows the same voltage divider circuit with an additional load resistance added.

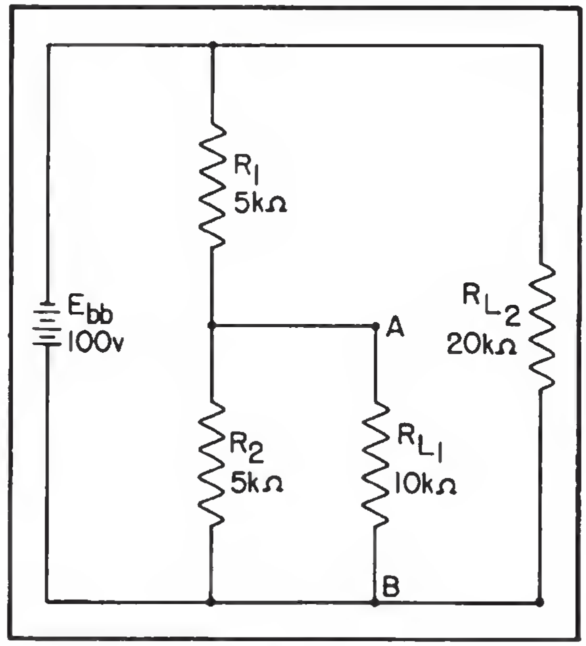

Figure 7-23 - Voltage divider with complete load applied.

The current through resistor R_{L2} can readily be computed since it is connected directly across the source voltage. This value is found as follows:

$$I_{R_{L_2}} = \frac{E_{bb}}{R_{L2}} = \frac{100}{20\times10^3} = 5ma$$

The current flow through resistor R_1 was found to be 12ma. The total current is:

$$I_t = I_{R1} + I_{RL2}$$

$$I_t = 12ma + 5ma$$

$$I_t = 17ma$$

The variation of voltages and currents found in the previous examples are undesirable in a voltage divider. It must be designed to provide voltages that are as stable as possible. A voltage divider consisting of two resistors will be designed using the circuit configuration shown in Figure 7-24. The supply voltage is two hundred volts. It is desired to furnish voltages of fifty and two hundred volts to two loads drawing six and eighteen milliamperes respectively.

Assume bleeder current to be ten percent of the required load current.

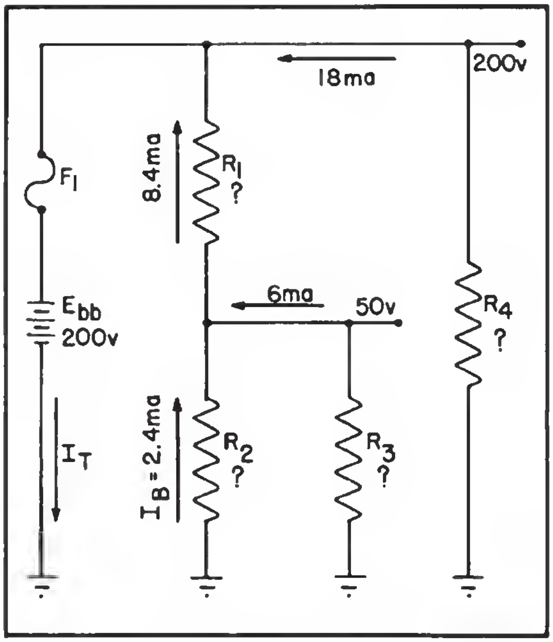

Figure 7-24 - Example circuit for proposed voltage divider.

Total load current is specified as twenty-four milliamperes. The bleeder current, therefore should be:

$$I_b = 10\%\ I_L$$

$$I_b = 10\% \times 24\text{ma}$$

$$I_b = 2.4\text{ma}$$

The bleeder current and the current through resistor R_3 combine and both currents flow through R_1. This current value may be computed:

$$I_{R_1} = I_b + I_{R_3}$$

$$I_{R_1} = 2.4\text{ma} + 6\text{ma}$$

$$I_{R_1} = 8.4\text{ma}$$

The total current may also be determined:

$$I_t = 8.4\text{ma} + 18\text{ma}$$

$$I_t = 26.4\text{ma}$$

The resistance values of R3 and R4 must be as follows:

$$R_3 = \frac{E_{R_3}}{I_{R_3}} = \frac{50}{6 \times 10^{-3}} = 8.33\text{k ohms}$$

$$R_4 = \frac{E_{R_4}}{I_{R_4}} = \frac{200}{18 \times 10^{-3}} = 11.1\text{k ohms}$$

Computing for R_1 and R_2:

$$R_1 = \frac{E_{R_1}}{I_{R_1}} = \frac{150}{8.4 \times 10^{-3}} = 17.85\text{k ohms}$$

$$R_2 = \frac{E_{R_2}}{I_{R_2}} = \frac{50}{2.4 \times 10^{-3}} = 20.82\text{k ohms}$$

Q13. When a current drawing device is connected across a resistor in a voltage divider, what is the effect upon the voltage applied to that device?

Q14. If the circuit shown in Figure 7-24 is fused at five hundred milliamps and resistor R_4 is shorted, what happens in the circuit? What is the total resistance of the circuit with resistor R_4 shorted?

SPECIAL NETWORK TECHNIQUES

The circuit solutions studied up to this point have been accomplished mainly through the use of formulas derived from Ohm's law. Like many other fields of science, electronics has its share of special short-cut methods. These methods, however, must be reserved until enough background theory has been presented to make their use worthwhile. The remaining section of this chapter will therefore be devoted to methods of solution which either simplify circuit calculations, or allow us to solve circuits which cannot be solved by ordinary methods.

7-14. Loop Analysis

LOOP ANALYSIS is a valuable method of circuit analysis in which Kirchhoff's voltage law is the key to the solution. In this method, two or more equations are formed which are then solved simultaneously.

Figure 7-25 shows a network containing five resistors and a source. This network will not actually be solved but is included so that the terms and procedures can be defined. In solv-

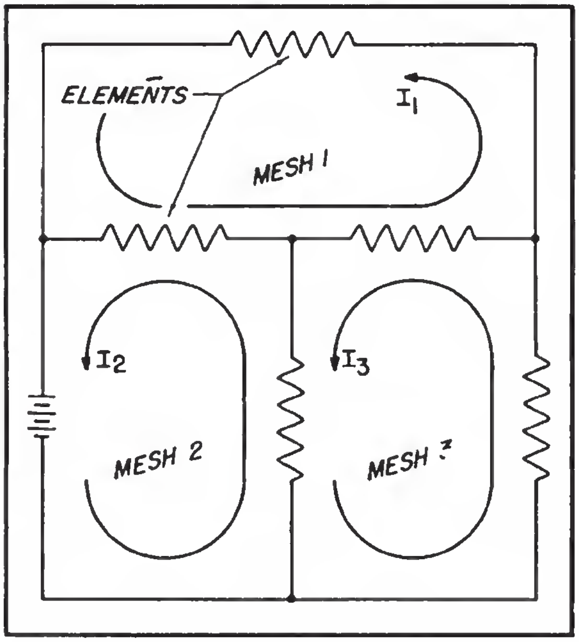

Figure 7-25 - A three mesh network.

ing this circuit by loop analysis, three currents are assumed as shown. Each current is arbitrarily assigned a COUNTER-CLOCKWISE direction (the true direction is unimportant at this time). Each of the three closed current paths is called a MESH. The individual circuit components (resistors) which form the meshes are called ELEMENTS.

To solve the circuit in Figure 7-25, three equations are formed, one for each mesh. The number of equations required is always equal to the number of meshes. These equations are then solved simultaneously.

7-15. A Typical Solution

In this section the combination circuit shown in Figure 7-26 will be solved using the loop method of analysis. Notice that the given circuit is a two mesh circuit and therefore two equations are required for the solution.

To begin the solution, a current circulating in a counter-clockwise direction is assumed in each mesh. In addition, it is assumed that these currents cause voltage drops across the circuit resistors. Polarities are then assigned to each resistor, according to the direction of current flowing through the resistor. Notice that resistor R_2 carries two currents which flow in opposite directions. A separate set of polarity signs is used for the voltage drops caused by each of these currents. After assigning currents and polarities to the circuit the voltage equations can be formed.

Recalling Kirchhoff's statement that the sum of the EMF's and voltage drops around any closed loop is equal to zero, an equation can be formed for loop ABEF of Figure 7-26. This equation is written starting at point A and trac-

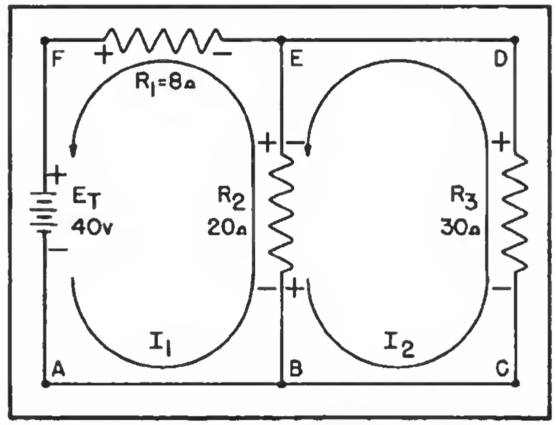

Figure 7-26 - Example circuit.

ing around the loop in the direction of assumed current. The polarities used for each voltage drop in the equation are those found following the component traced through. For example, in tracing through R_1 from E to F the positive polarity sign is used. (For those needing a review of Kirchhoff's voltage equations see section 6-19). The equation for loop ABEF is therefore:

ABEF: $+20I_1 - 20I_2 + 8I_1 - 40 = 0$ (1)

simplifying: $28I_1 - 20I_2 = 40$ (2)

Notice that in passing through R_2, two voltage drops of opposite polarity are encountered. Both of these drops ($+20I_1$ and $-20I_2$) must be included in the equation along with their proper polarities.

Next, an equation is written for loop BCDE. This equation is:

BCDE: $+30I_2 + 20I_2 - 20I_1 = 0$ (3)

simplifying: $-20I_1 + 50I_2 = 0$ (4)

Again notice that two opposing voltage drops ($+20I_2$ and $-20I_1$) were included for R_2.

Equations (2) and (4) repeated below, are now solved simultaneously to obtain I_1 and I_2.

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A13. The voltage applied to the device will be less than the amount across the divider resistor before the connection.

A14. The fuse would burn out opening the circuit. The total resistance would be zero the instant the resistor shorted and would result in an infinite resistance when the fuse opens.

$$28I_1 - 20I_2 = 40 \qquad (2)$$

$$-20I_1 + 50I_2 = 0 \qquad (4)$$

In order to eliminate I_2, equation (2) is multiplied by five and equation (4) is multiplied by two. The resulting equations (5) and (6) are then added.

$$140I_1 - 100I_2 = 200 \qquad (5)$$

$$-40I_1 + 100I_2 = 0 \qquad (6)$$

$$100I_1 = 200$$

Dividing both sides by 100:

$$I_1 = \frac{200}{100}$$

$$I_1 = 2 \text{ amps}$$

To obtain the value of I_2, 2 amps is now substituted into equation (4) and in place of I_1.

$$-20x2 + 50I_2 = 0$$

$$-40 + 50I_2 = 0$$

$$50I_2 = 40$$

$$I_2 = 0.8 \text{ amps}$$

Thus, current I_1 is 2 amps and current I_2 is 0.8 amps. The voltage drops can now be evaluated using these currents and Ohm's law as follows:

$$E_{R_1} = I_1R_1$$

$$E_{R_1} = 2 \times 8$$

$$E_{R_1} = 16 \text{ volts}$$

Notice that the actual current through R_2 is the algebraic sum of the two opposing currents. The voltage across R_2 is therefore:

$$E_{R_2} = (I_1-I_2)R_2$$

$$E_{R_2} = 1.2 \times 20$$

$$E_{R_2} = 24 \text{ volts}$$

$$E_{R_3} = I_2R_3$$

$$E_{R_3} = 0.8 \times 30$$

$$E_{R_3} = 24 \text{ volts}$$

Q15. How many loops should be traced when determining unknown circuit quantities by the loop analysis method?

Q16. What is the purpose of expressing voltage drops in terms of the product of current and resistance?

7-16. Multiple Source Circuits

Quite frequently, networks containing more than one source must be solved. Although a circuit of this type may look complicated, the solution is no more difficult than the one discussed in section 7-15. In fact, the same method of solution is used in both single and multiple source circuits.

Figure 7-27 shows a multiple source circuit which will be used in the example solution. In the diagram a counter-clockwise current has been assumed in each mesh and polarities assigned accordingly. Note that R_2 has two op-

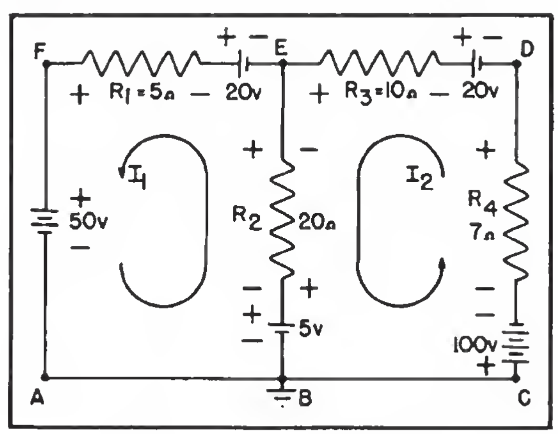

Figure 7-27 - Example multiple source circuit.

posing voltage drops, one for each current. The voltage equation for loop ABEF is:

$$+5 + 20I_1 - 20I_2 + 20 + 5I_1 - 50 = 0 \qquad (7)$$

simplifying: $$25I_1 - 20I_2 = 25 \qquad (8)$$

Loop BCDE:

$$-100 + 7I_2 + 20 + 10I_2 + 20I_2 - 20I_1 - 5 = 0 \qquad (9)$$

simplifying: $$-20I_1 + 37I_2 = 85 \qquad (10)$$

multiply (8) by 4: $$100I_1 - 80I_2 = 100 \qquad (11)$$
multiply (10) by 5: $$-100I_1 + 185I_2 = 425 \qquad (12)$$
add: $$+ 105I_2 = 525$$

$$I_2 = \frac{525}{105}$$

$$I_2 = 5 \text{ amps} \qquad (13)$$

substitute (13) in (8)

$$25I_1 - 20(5) = 25$$

$$25I_1 - 100 = 25$$

$$25I_1 = 125$$

$$I_1 = 5 \text{ amps} \qquad (14)$$

Had one of the above currents been negative this would have indicated an incorrectly assumed direction of current flow. The magnitude of current would be correct. Now that the currents are known, the voltage drops across the resistors can be calculated.

$$E_{R1} = I_1R_1$$

$$E_{R1} = 25 \text{ volts}$$

$$E_{R2} = (I_1 - I_2)R_2$$

$$E_{R2} = 0 \text{ volts}$$

Notice that equal and opposite currents flow through R_2 and no voltage drop occurs across it.

$$E_{R3} = I_2R_3$$

$$E_{R3} = 50 \text{ volts}$$

$$E_{R4} = I_2R_4$$

$$E_{R4} = 35 \text{ volts}$$

Q17. What is the significance of a negative value of current in the solution to a problem when the loop analysis method is used?

Q18. When writing loop equations is it necessary to trace over the same paths taken by the assumed currents?

7-17. Equivalent Circuits

In the analysis of many circuits the solution is primarily concerned with the computation of values for load current and load voltage. In most cases additional calculations are required as intermediate steps in the solution. The following discussion will show how many of these intermediate steps can be eliminated.

Let us now examine the load resistor (R_L) shown in Figure 7-28. This resistor is connected to a switch so that it can be connected across the terminals of either of the two circuits. When the switch is in the position illustrated, R_L is connected to circuit (A).

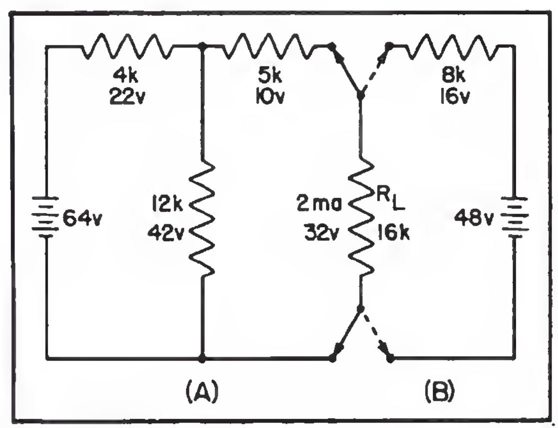

Figure 7-28 - Equivalent circuits.

By using a lengthy series of steps, the values of load current (2 ma) and load voltage (32 v) can be computed. Using the methods studied up to this time, computations of total resistance, total current, and various voltage drops would be required as intermediate steps of the solution. (An alternate method would be loop analysis.)

Keeping in mind the values of load voltage and current determined for circuit (A), assume the switch to be in the position which places R_L across the terminals of circuit (B). In this simple series circuit the load voltage and current can be easily determined. Notice that again the load voltage is 32 volts and the load

A15. As few as required in order to trace through all components at least once.

A16. Generally currents are to be solved for, hence voltage is expressed in terms of the unknown currents and resistance.

A17. The assumed direction of mesh current is incorrect.

A18. No. As long as each component is included at least once in the equations the correct result will be obtained.

---

current is 2 ma. Since the load voltage and current are the same regardless of which circuit is used, AS FAR AS THE LOAD IS CONCERNED CIRCUIT (B) COULD BE SUBSTITUTED FOR CIRCUIT (A). A circuit that may be substituted for another circuit is called an EQUIVALENT CIRCUIT. The purpose of this section is to show how a SIMPLE equivalent circuit can be developed for any COMPLEX circuit. This simple equivalent circuit is then used for the calculations instead of the original complex circuit. It should not be necessary to emphasize the hours of work that can be saved by utilizing an equivalent circuit.

7-18. Thevenin's Theorem

One of the most valuable equivalent circuits is one known as THEVENIN's EQUIVALENT CIRCUIT. This circuit is derived from Thevenin's Theorem, stated as follows:

Thevenin's Theorem: Any linear network of impedance and sources, if viewed from any two points in the network, can be replaced by an equivalent impedance Z_{th} in series with an equivalent voltage source E_{th}. (The Term impedance means any opposition to current flow and in dc circuits will be taken to mean resistance.)

According to this theorem ANY linear dc circuit regardless of its complexity can be replaced by a Thevenin's equivalent shown in Figure 7-29.

The process whereby a Thevenin's equivalent circuit is developed for a given network is best illustrated by an example.

Let us assume that the circuit in Figure 7-30A is to be used to develop a Thevenin's equivalent circuit. Basically the problem consists of finding values for E_{th} and Z_{th}. These quantities can be found using the following procedure.

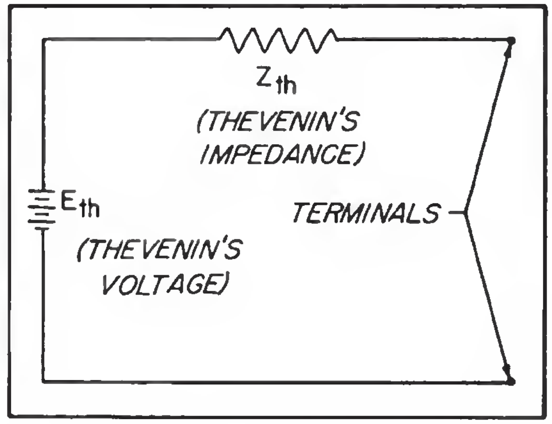

Figure 7-29 - Thevenin's equivalent circuit.

APPLICATION OF THEVENIN'S THEOREM

1. Disconnect the section of the circuit considered as the load (R_L in Figure 7-30A).

2. By measurement or calculation determine the voltage that would appear between the load terminals with the load disconnected (terminals X and Y). This open circuit voltage is called Thevenin's voltage (E_{th}).

3. Replace each source within the circuit by its internal impedance. (A constant voltage source such as a battery is replaced with a short, while a constant current source is replaced with an open. (See B of Figure 7-30.)

4. By measurement or calculation determined the impedance (resistance) the load would see, looking back into the network from the load terminals. (B of Figure 7-30.) This is Thevenin's impedance (Z_{th}).

5. Draw the equivalent circuit consisting of R_L and Z_{th} in series, connected across source E_{th} (C of Figure 7-30). Solve for the load current and voltage.

Q19. Is Thevenin's voltage the same value as the original source voltage?

7-19. A Typical Solution

In the following solution, the load voltage will be computed using loop analysis. The circuit will then be solved a second time using a Thevenin's equivalent circuit. The two methods can thus be compared as to results and ease of computation.

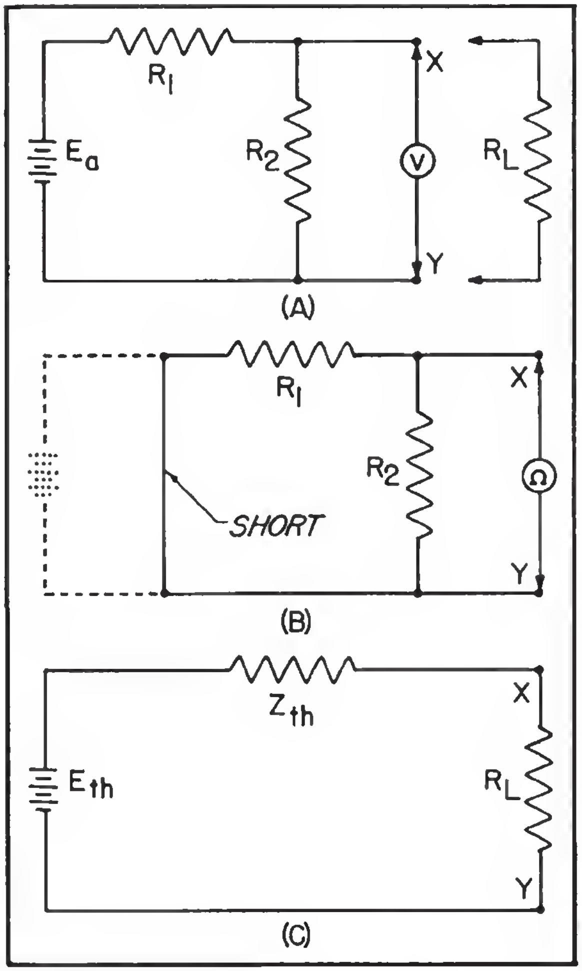

Figure 7-30 - Developing a Thevenin's equivalent.

Figure 7-31 shows a three mesh circuit for which the output voltage E_L is to be determined. Currents are assumed in each mesh and appropriate polarities are assigned. The voltage equations are then written as follows:

ABGH: $$+10I_1 - 10I_2 - 110 = 0 \quad (15)$$

$$10I_1 - 10I_2 = 110 \quad (16)$$

BCFG: $$+30I_2 - 30I_3 + 20I_2 + 10I_2 - 10I_1 = 0 \quad (17)$$

$$-10I_1 + 60I_2 - 30I_3 = 0 \quad (18)$$

CDEF: $$+10I_3 + 30I_3 - 30I_2 = 0 \quad (19)$$

$$-30I_2 + 40I_3 = 0 \quad (20)$$

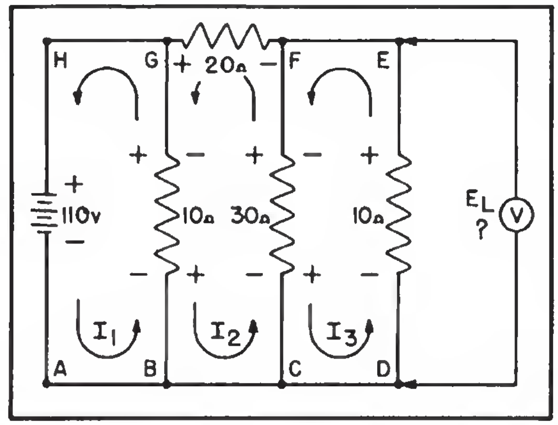

Figure 7-31 - Example circuit.

Adding (16) to (18):

$$\begin{array}{r} 10I_1 - 10I_2 \qquad\quad = 110 \\ -10I_1 + 60I_2 - 30I_3 = \ \ 0 \\ \hline 50I_2 - 30I_3 = 110 \end{array} \quad (21)$$

Multiplying (20) by 3: $-90I_2 + 120I_3 = 0$
Multiplying (21) by 4: $200I_2 - 120I_3 = 440$
Adding: $110I_2 = 440$ (22)

$$I_2 = 4 \text{ amps} \quad (23)$$

Substituting (23) into (20)

$$-30(4) + 40I_3 = 0$$

$$-120 + 40I_3 = 0$$

$$40I_3 = 120$$

$$I_3 = 3 \text{ amps} \quad (24)$$

Substituting (23) into (16)

$$10I_1 - 10(4) = 110$$

$$10I_1 - 40 = 110$$

$$10I_1 = 150$$

$$I_1 = 15 \text{ amps} \quad (25)$$

Once all three currents are known the voltages are computed and added for each loop as a check. If the computed voltages around each loop add up to zero the computed currents are correct. The output voltage E_L is then:

A19. Not usually. In some simple circuits it can be, however.

$$E_L = I_3 R_L$$

$$E_L = 30 \text{ volts}$$

Most people will agree that the above solution is long and tedious. The same circuit will now be solved through the use of a Thevenin's equivalent circuit. The procedure is as follows:

1. Disconnect the load as shown in A of Figure 7-32.

2. Compute E_{th}, the no load (open circuit) voltage between terminals E and D. This voltage is the same as the voltage across R_3. Since 110 volts are applied to R_2 and R_3 in series the voltage across R_3 is three-fifths of 110 volts or 66 volts.

3. Replace the source with its internal impedance. In this case the source is a battery (constant voltage source) and is replaced with a short as in B of Figure 7-32. This shorts out both the battery terminals and R_1 resulting in the circuit shown in C of Figure 7-32.

   NOTE: The internal resistance of a flash light cell is approximately 0.005 ohm. Thus, the internal resistance of a battery is usually considered to be zero ohms.

4. Determine the resistance (Z_{th}) the load would see "looking back" into the network from terminals E and D. Notice that in C of the Figure, two separate paths exist between terminals E and D. One of these paths is through R2 and the other is through R3, indicating the two resistors to be in parallel. Since R_2 and R_3 are in parallel this resistance Z_{th} is:

$$Z_{th} = \frac{R_2 R_3}{R_2 + R_3}$$

$$Z_{th} = \frac{20 \times 30}{20 + 30}$$

$$Z_{th} = 12 \text{ ohms}$$

5. Draw the equivalent circuit and connect the load resistance as in D of Figure 7-32, including the values obtained for E_{th} and Z_{th}. Using Ohm's law, solve for the load current and voltage.

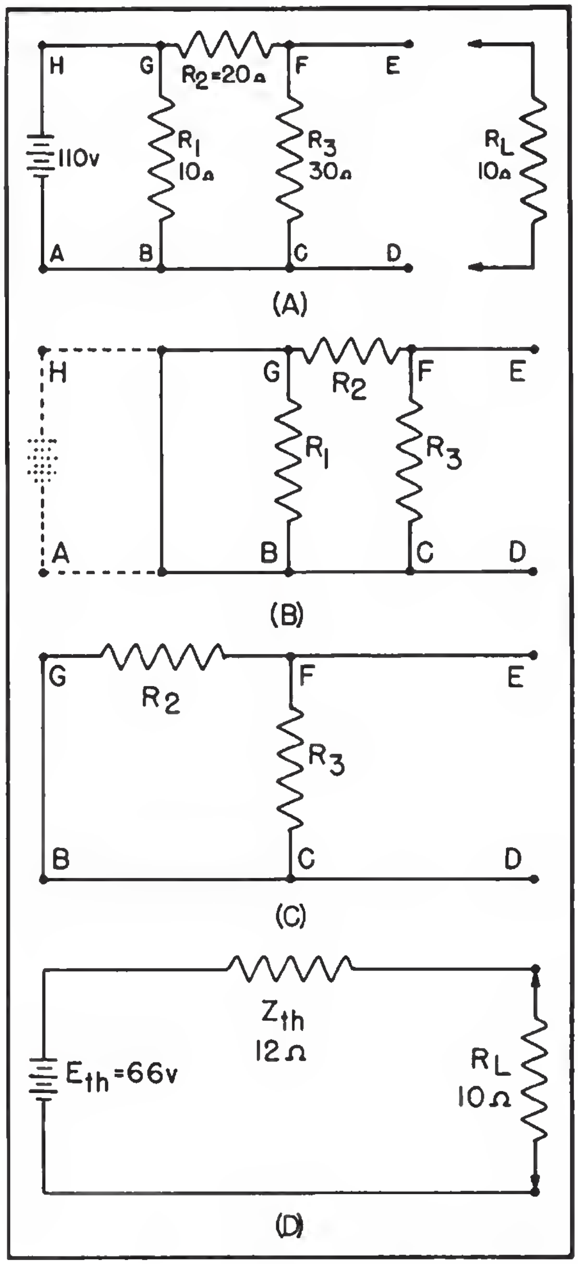

Figure 7-32 - Evolution of the equivalent circuit.

$$I_L = \frac{E_{th}}{Z_{th} + R_L}$$

$$I_L = \frac{66}{22}$$

$I_L = 3$ amps

Notice that the load currents (I_3 in the loop analysis and I_L in Thevenin's equivalent) are identical.

$$E_L = I_L R_L$$

$$E_L = 3 \times 10$$

$$E_L = 30 \text{ volts}$$

This is the same value of voltage found by loop analysis. At this point one should stop and compare the labor required by each method in order to reach a solution. Once the steps used in applying Thevenin's theorem are learned, this method is by far the simpler of the two methods.

7-20. Voltage Divider Equation

As an aid to the application of Thevenin's equivalent circuit, an equation can be derived which will yield the load voltage in one simple calculation. This equation (the derivation will be left as a problem for the student) is:

$$E_L = \frac{E_{th} R_L}{Z_{th} + R_L} \qquad (7\text{-}10)$$

To illustrate the use of equation (7-10) the Thevenin equivalent will be developed for the circuit in Figure 7-33. As before, the load circuit will be opened to determine E_{th}, the open circuit load voltage. With the switch in Figure 7-33 open, no load current flows through R_L or R_3. The voltage between X and Y is therefore the same as the voltage across R_2. Applying the voltage divider formula this voltage is found to be:

$$E_{R2} = \frac{E_a R_2}{R_1 + R_2}$$

$$E_{R2} = \frac{100 \times 30}{50}$$

$$E_{R2} = 60 \text{ volts}$$

Since this is the open circuit load voltage, this voltage is E_{th}.

$$E_{th} = 60 \text{ volts}$$

Next the source is replaced with a short circuit. This places R_1 and R_2 in parallel and the impedance Z_{th} looking back into the network is:

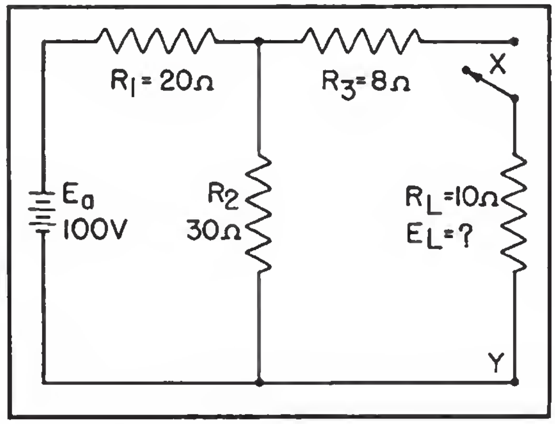

Figure 7-33 - Example circuit.

$$Z_{th} = R_3 + \frac{R_1 R_2}{R_1 + R_2}$$

$$Z_{th} = 8 + \frac{20 \times 30}{50}$$

$$Z_{th} = 20 \text{ ohms}$$

The Thevenin's equivalent circuit is drawn and the load connected as in Figure 7-34. In one step the output voltage across the load can be found as follows:

$$E_L = \frac{E_{th} R_L}{Z_{th} + R_L} \qquad (7\text{-}10)$$

$$E_L = \frac{60 \times 10}{30}$$

$$E_L = 20 \text{ volts}$$

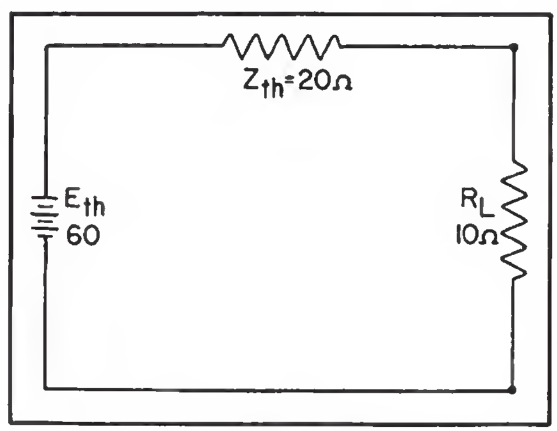

Figure 7-34 - Thevenin's equivalent for Figure 7-33.

Using Thevenin's equivalent circuit and the voltage divider equation as tools, certain complex circuits can be quickly solved. This technique should not be forgotten as it will be a time saving aid in future chapters.

7-21. Norton's Theorem

Another important theorem that can be used as an aid in solving complex circuits is called NORTON's THEOREM. This theorem is similar to Thevenin's and is stated as follows:

Norton's Theorem: Any linear network of impedance and sources, if viewed from any two points in the network, can be replaced by an equivalent impedance Z_{th} in shunt with an equivalent current source I_n.

This equivalent circuit is shown in Figure 7-35. Notice that the impedance Z_{th} is placed in shunt (parallel) with a constant current source. The impedance Z_{th} is the same impedance used in Thevenin's equivalent circuit.

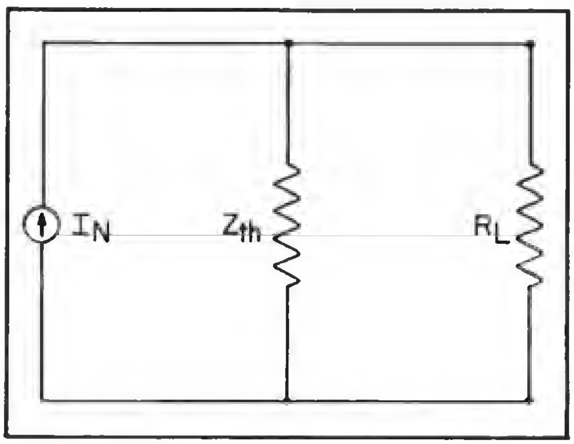

Figure 7-35 - Norton's equivalent circuit.

To illustrate the application of Norton's theorem, a Norton's equivalent circuit will be developed for the network shown in Figure 7-36. The quantities Z_{th} and I_n can be found as follows:

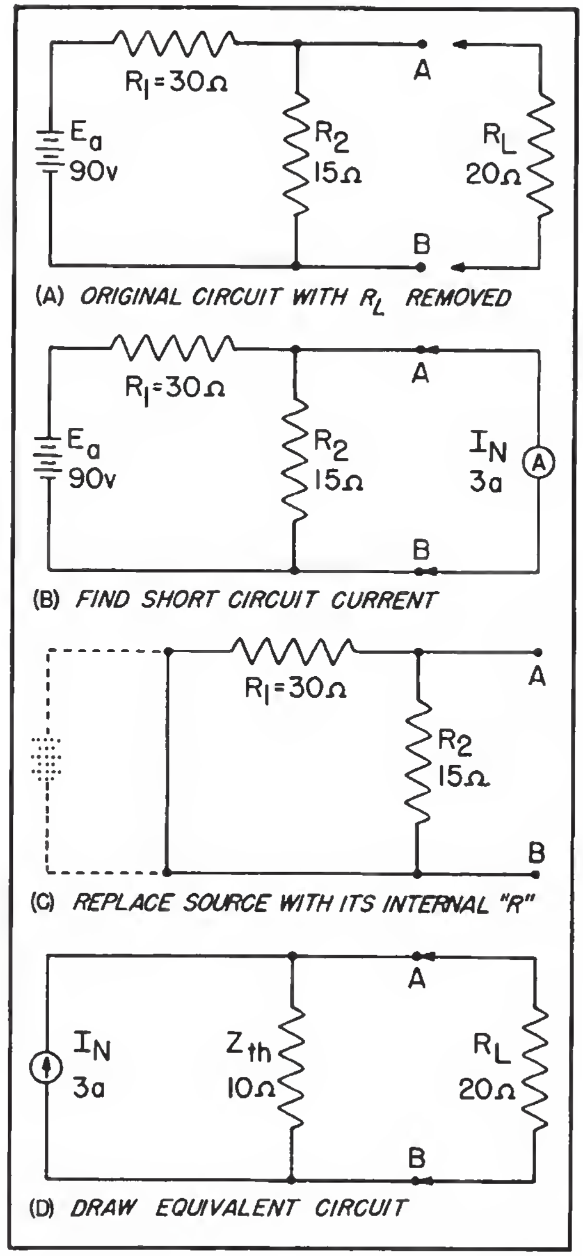

Figure 7-36 - Evolution of Norton's equivalent circuit.

APPLICATION OF NORTON'S THEOREM

1. Disconnect the section of the circuit considered as the load (R_L in Figure 7-36A).

2. By measurement or calculation determine the current that would flow through a wire connected between the load terminals (A and B of Figure 7-36B). This short-circuit load current is Norton's current (I_n).

3. Remove short from load terminals. Replace each source within the network with its internal impedance (the battery in Figure 7-36C is replaced with a short).

4. By measurement or calculation determine the impedance Z_{th} looking back into the network. (Same as for Thevenin's equivalent.)

5. Draw the equivalent circuit consisting of R_L, Z_{th}, and source I_n all in parallel (D of Figure 7-36) and then solve for the desired quantities.

As an aid to the application of Norton's theorem, a current divider equation can be derived which will yield the load current in one calculation. Using the notation from Norton's equivalent circuit this equation is:

$$I_L = \frac{I_n Z_{th}}{Z_{th}+R_L} \qquad (7\text{-}11)$$

The current through the short (I_n) in Figure 7-36B is 3 amps, since the short effectively places R_1 directly across the source. With I_n equal to 3 amps and Z_{th} equal to 10 ohms, the load current I_L is:

$$I_L = \frac{I_n Z_{th}}{Z_{th}+R_L} \qquad (7\text{-}11)$$

$$I_L = \frac{3 \times 10}{10+20}$$

$$I_L = 1 \text{ amp}$$

Should it be desired to develop the Thevenin's equivalent circuit, E_{th} can be easily determined. The Thevenin's and Norton's equivalent circuits are closely related such that:

$$E_{th} = I_n Z_{th} \qquad (7\text{-}12)$$

E_{th} for Figure 7-36 is therefore:

$$E_{th} = I_n Z_{th}$$

$$E_{th} = 3 \times 10$$

$$E_{th} = 30 \text{ volts}$$

Thus, if either equivalent circuit is known it is a simple matter to convert to the other. Usually a Norton's equivalent circuit is used when the load current is desired, and a Thevenin's equivalent circuit is used when the load voltage is required.

7-22. Bridge Circuits

A resistance bridge circuit in its simplest form is shown in Figure 7-37. Two identical resistors, R_1 and R_2, are connected in parallel across a 20 volt source. The network becomes a bridge circuit when a cross connection, or "bridge" is placed between the two resistors.

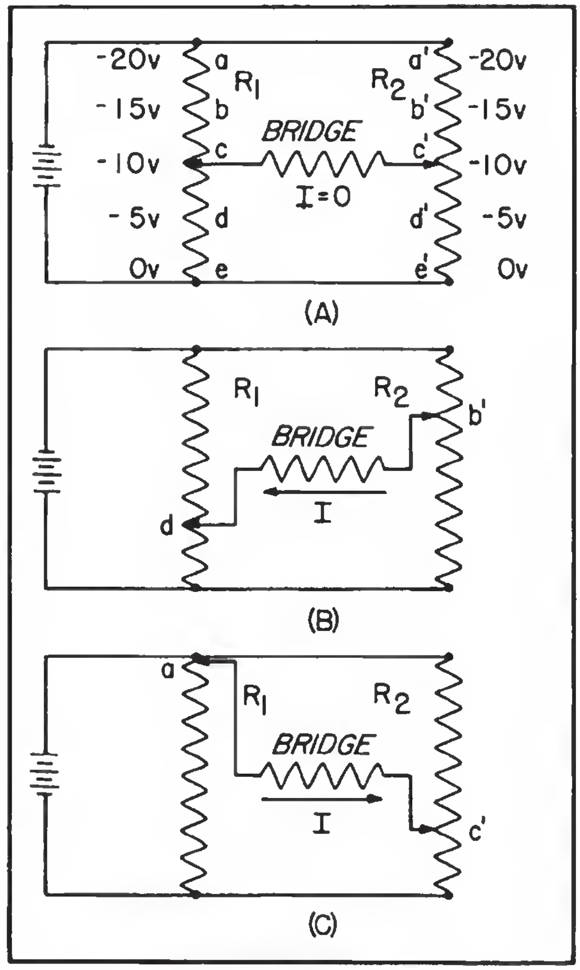

Figure 7-37 - Simple resistance bridges.

Voltage across both resistors is dropped at the same rate, because the resistors are identical. Therefore, points a-a', b-b', c-c', and d-d' are at equal potentials. If the bridge is connected between points of equal potential, as in Figure 7-37A, no current will flow through the bridge. However, if the bridge is connected between points of unequal potential, current will flow from the more negative to the less negative end, as shown in Figure 7-37B. In B, current flows right-to-left from b' to d. In C, current flows left-to-right from a to c'. Thus, it can be seen that the direction of bridge current is controlled by the difference in potential between the two ends of the bridge resistor. When the bridge resistor is across points of equal potential, no current flows through the bridge resistor and the bridge is said to be BALANCED. When it is across unequal potentials, current flows through the bridge resistor and the bridge

is said to be UNBALANCED. The bridge may be unbalanced in either or both of two ways (1) by connecting the bridge to unequal potentials or (2) by using resistors of unequal value.

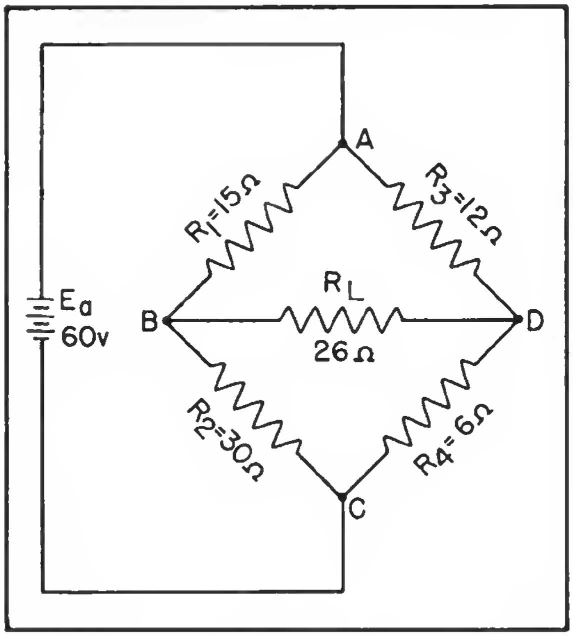

Figure 7-38 - Example bridge circuit.

7-23. Solution of a Bridge Circuit

Without a knowledge of Thevenin's theorem a bridge circuit would be difficult to solve. A solution could be obtained by loop analysis but only at the expense of much time and labor. The following example will illustrate the application of Thevenin's theorem to a bridge circuit.

Example. Find the voltage across and the current through bridge resistor R_L in Figure 7-38. The bridge resistor is removed so that the open circuit voltage E_{th} can be found. The circuit now appears as in Figure 7-39. The voltage E_{th} is actually the algebraic sum of the voltages across R_2 and R_4. These voltages can be found using the voltage divider equation and are:

$$E_{R2} = \frac{E_a R_2}{R_1 + R_2}$$

$$E_{R2} = \frac{60 \times 30}{45}$$

$$E_{R2} = 40 \text{ volts}$$

and:

$$E_{R4} = \frac{E_a R_4}{R_3 + R_4}$$

$$E_{R4} = \frac{60 \times 6}{18}$$

$$E_{R4} = 20 \text{ volts}$$

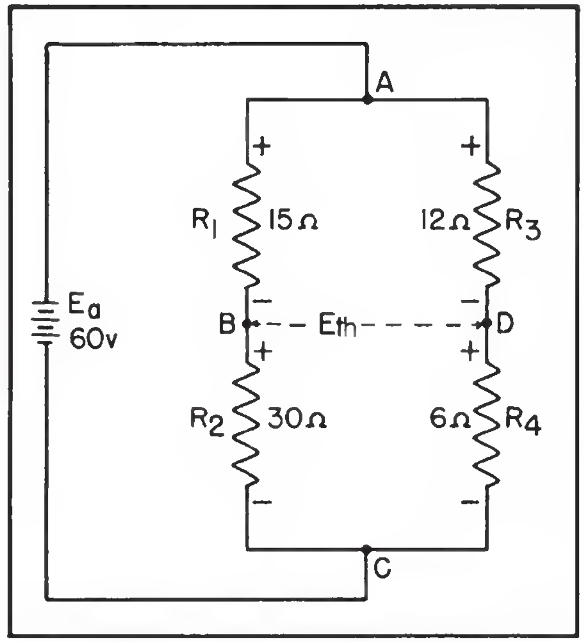

Figure 7-39 - Bridge with R_L removed.

The voltage at B with respect to D can be found by starting at D and tracing around to B, adding up the voltage drops along the route. Thus, starting at D the voltage drop across R_4 is -20v. Continuing around the circuit the voltage drop across R_2 is +40 volts. Therefore, the voltage at B with respect to D is:

$$E_{BD} = -20 + 40$$

$$E_{BD} = +20 \text{ volts}$$

This +20 volts is E_{th}.

To determine Z_{th}, the battery is replaced with a short. The circuit now appears as in Figure 7-40A, since placing a short across the battery terminals is the same as placing a short between points A and C of the bridge. The circuit can be redrawn as in B of Figure 7-40. This drawing shows that R_1 and R_2 are actually in parallel and are in turn in series with the parallel combination of R_3 and R_4. The impedance Z_{th} is therefore equal to the sum of the equivalent resistances of the two parallel groups or:

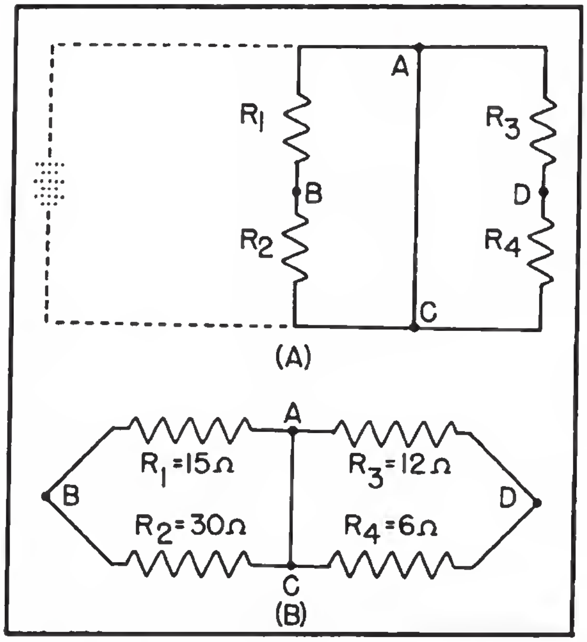

Figure 7-40 - Finding Thevenin's impedance.

$$Z_{th} = \frac{R_1R_2}{R_1+R_2} + \frac{R_3R_4}{R_3+R_4}$$

$$Z_{th} = \frac{15\text{x}30}{45} + \frac{12\text{x}6}{18}$$

$$Z_{th} = 10 + 4$$

$$Z_{th} = 14 \text{ ohms}$$

The complete Thevenin's equivalent including the values of E_{th}, Z_{th} and R_L is shown in Figure 7-41.

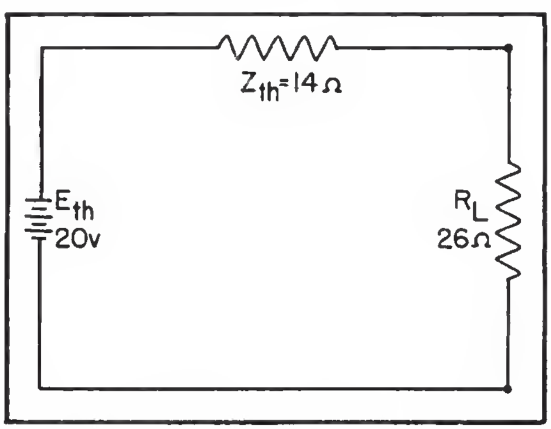

Figure 7-41 - Thevenin's equivalent for the bridge circuit.

The voltage across the load is:

$$E_L = \frac{E_{th}R_L}{Z_{th} + R_L} \tag{7-10}$$

$$E_L = \frac{20\text{x}26}{40}$$

$$E_L = 13 \text{ volts}$$

The load current is:

$$I_L = \frac{E_L}{R_L}$$

$$I_L = \frac{13}{26}$$

$$I_L = 0.5 \text{ amp}$$

These values of voltage and current computed from the equivalent circuit are the same values of load voltage and current that would exist in the original circuit.

In some applications it may be necessary to find values for the current and voltage in one of the arms of a bridge circuit. Again a Thevenin's equivalent can be used to simplify the solution.

Example. Thevenize the bridge circuit shown in Figure 7-42 and solve for the load voltage (E_L).

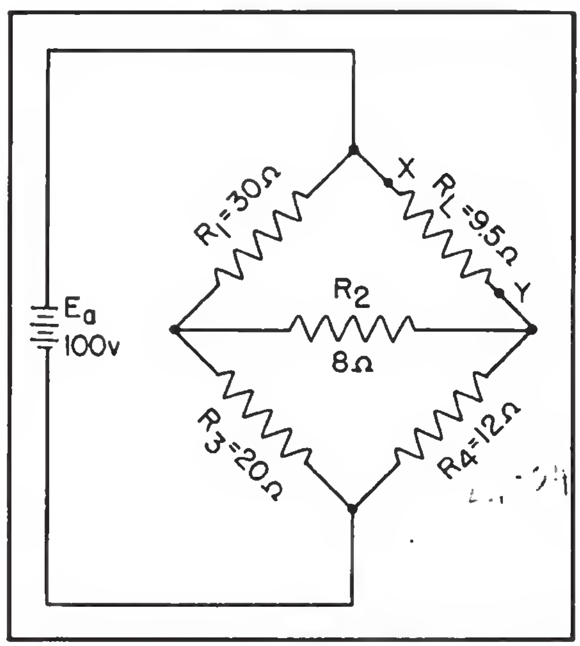

Figure 7-42 - Example bridge circuit.

Remove the load resistor (R_L). The circuit now appears as in (A) of Figure 7-43, which can be redrawn as in (B) of Figure 7-43.

Solve for E_{th} the open circuit load voltage. This can be done in two steps using the voltage divider equations as follows:

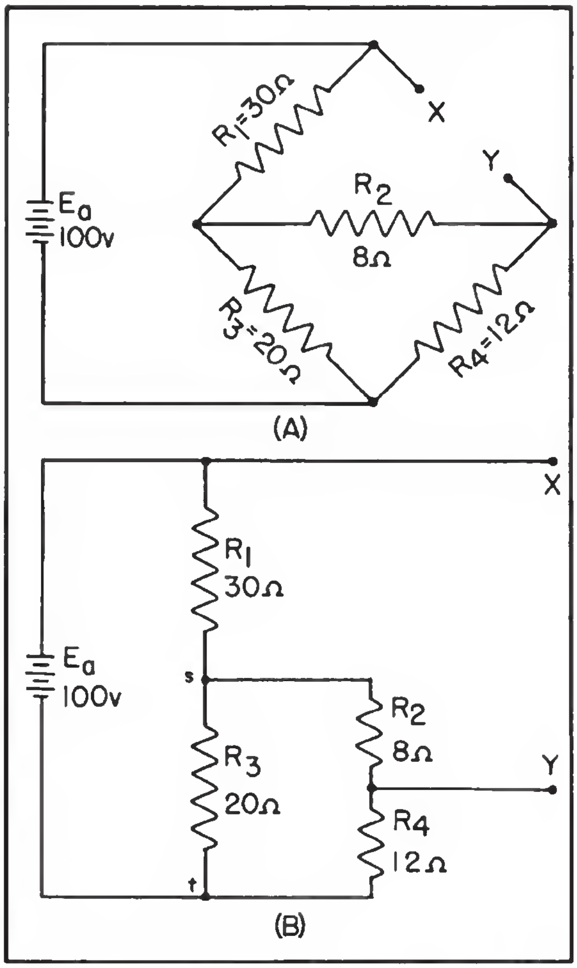

Figure 7-43 - Bridge with load removed.

First find the equivalent resistance of the network consisting of R_3, R_2, and R_4. This is:

$$R_{eq} = \frac{R_3(R_2+R_4)}{R_3+(R_2+R_4)}$$

$$R_{eq} = \frac{20(8+12)}{20+(8+12)}$$

$$R_{eq} = 10 \text{ ohms}$$

Using the voltage divider formula, find the voltage drop across R_{eq} (from (s) to (t) in Figure 7-43B).

$$E_{st} = \frac{E_a R_{eq}}{R_1+R_{eq}}$$

$$E_{st} = \frac{100 \times 10}{40}$$

$$E_{st} = 25 \text{ volts}$$

The voltage across R_1 is therefore:

$$E_{R1} = E_a - E_{st}$$

$$E_{R1} = 100 - 25$$

$$E_{R1} = 75 \text{ volts}$$

Next, considering E_{st} as the source voltage for R_2 and R_4 solve for the voltage across R_2.

$$E_{R2} = \frac{E_{st} \times R_2}{R_4 + R_2}$$

$$E_{R2} = \frac{25 \times 8}{20}$$

$$E_{R2} = 10 \text{ volts}$$

Thevenin's voltage (E_{th}) is the open circuit voltage between points (X) and (Y). This voltage is the algebraic sum of the voltages across R_1 and R_2.

$$E_{th} = E_{R1} + E_{R2}$$

$$E_{th} = 75 + 10$$

$$E_{th} = 85 \text{ volts}$$

Determine the impedance (Z_{th}) looking back into the load terminals (X) and (Y) as follows. Replace the battery with a short. The circuit now appears as in Figure 7-44A. Rotating the position of R_1 downward the circuit can be redrawn as in Figure 7-44B. This circuit can be further rearranged so as to appear as in (C) of Figure 7-44.

The impedance (Z_{th}) looking back into terminals (X) and (Y) is the equivalent resistance of R_1 and R_3 plus the resistance of R_2, all in parallel with R_4. Z_{th} is found as follows:

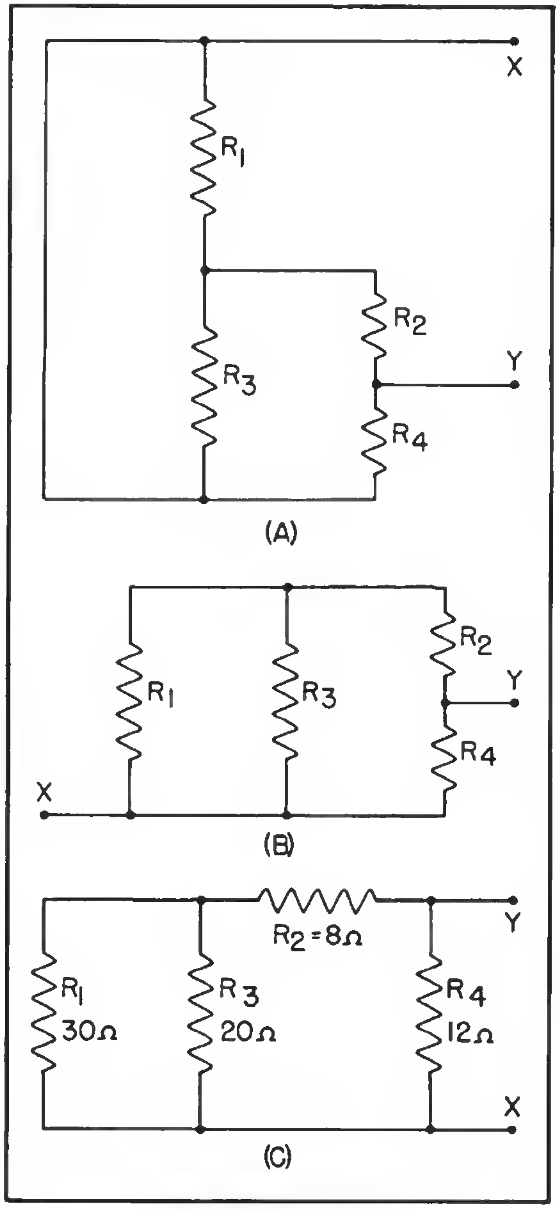

Figure 7-44 - Determining Z_{th}.

$$Z_{th} = \frac{R_4\left[R_2 + \left(\frac{R_1R_3}{R_1+R_3}\right)\right]}{R_4 + \left[R_2 + \left(\frac{R_1R_3}{R_1+R_3}\right)\right]}$$

$$Z_{th} = \frac{12\left[8 + \left(\frac{30 \times 20}{30+20}\right)\right]}{12 + \left[8 + \left(\frac{30 \times 20}{30+20}\right)\right]}$$

$$Z_{th} = \frac{12(8 + 12)}{12 + (8 + 12)}$$

$$Z_{th} = \frac{12 \times 20}{32}$$

$$Z_{th} = 7.5 \text{ ohms}$$

Draw the equivalent circuit including the values for E_{th}, Z_{th} and R_L as shown in Figure 7-45.

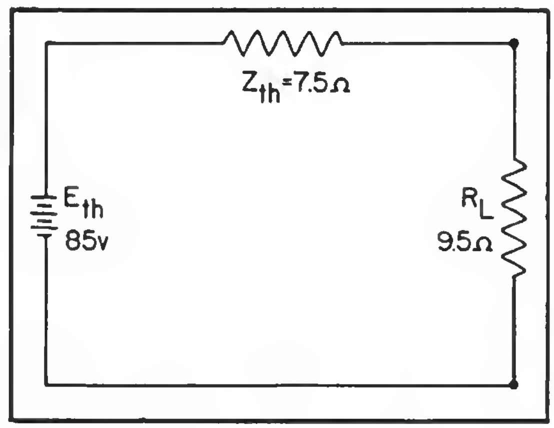

Figure 7-45 - Thevenin's equivalent for bridge.

Using the voltage divider formula solve for the load voltage (E_L).

$$E_L = \frac{E_{th}R_L}{Z_{th} + R_L}$$

$$E_L = \frac{85 \times 9.5}{17}$$

$$E_L = 47.5 \text{ volts}$$

At this point the student has at his command, many different methods of solving dc circuits. He should not stick to one method alone. Instead he should apply the method which is best suited to the particular problem at hand. In the following chapter a foundation will be laid for the study of ac circuits.

EXERCISE 7

1. Explain the difference between a series circuit and a parallel circuit.
2. On what factors does the amount of current in each branch of a parallel circuit depend?
3. What effect does a change of resistance in one branch of a pure parallel circuit have on the amount of current in the other branches?
4. What is the equivalent resistance of a 15 kilohm resistor and a 35 kilohm resistor connected in parallel?
5. Using Figure 7-46 find I_1, I_2, I_t and the voltage across each resistor.

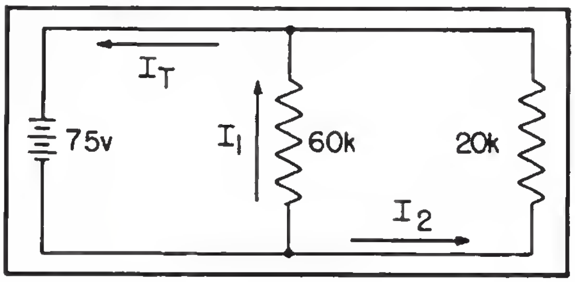

Figure 7-46

6. Using Figure 7-47 find the value of R_2, the total resistance, the total current, and the power supplied by the source.

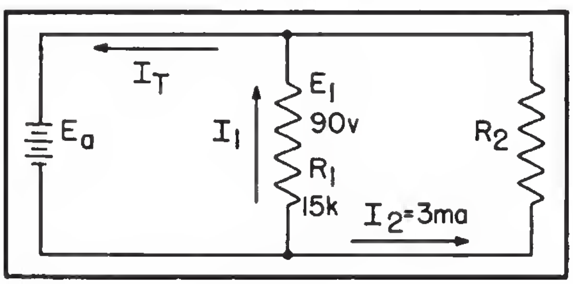

Figure 7-47

7. Using Figure 7-48 find I_1, I_2, the applied voltage, the total resistance, and the power dissipated by each resistor.

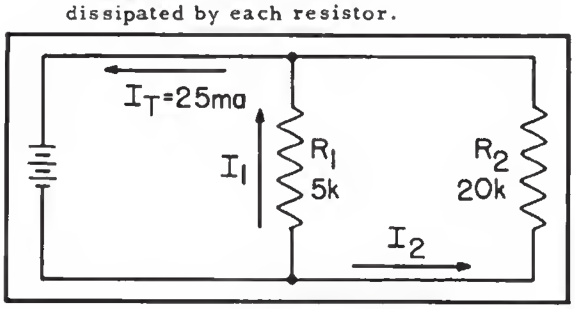

Figure 7-48

8. If currents of 5, 10, and 20 milliamperes enter a junction, what is the value of the current leaving the junction?

9. Reduce the circuit in Figure 7-49 to one containing a source and a single resistor (include values).

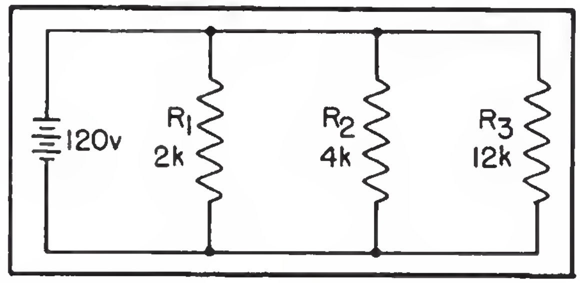

Figure 7-49

10. What is the conductance of a parallel circuit in which the source voltage is 100 volts and the total current is 20 ma?

11. Find the load voltages and the supply voltage for the voltage divider in Figure 7-50.

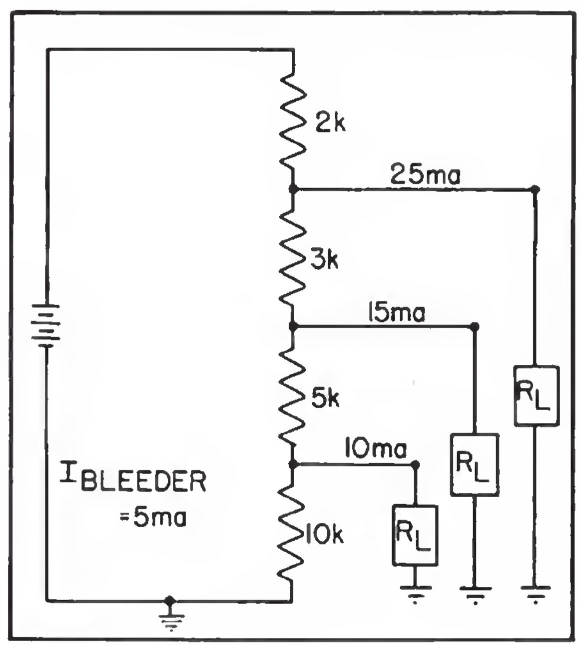

Figure 7-50

12. Using the circuit of Figure 7-51 find:

R_t = ______ I_{R1} = ______ P_{R3} = ______

I_t = ______ I_{R2} = ______ P_t = ______

E_{R1} = ______ I_{R3} = ______

E_{R2} = ______ P_{R1} = ______

E_{R3} = ______ P_{R2} = ______

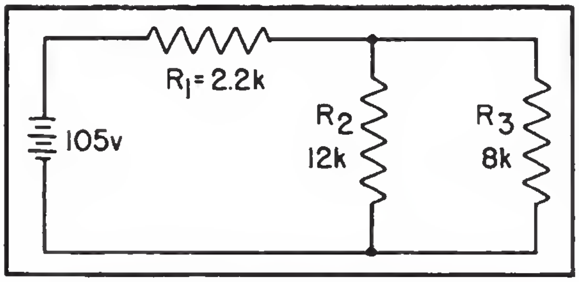

Figure 7-51

13. Write the four designated loop equations for the circuit shown in Figure 7-52. Reduce the equations to simplest terms.

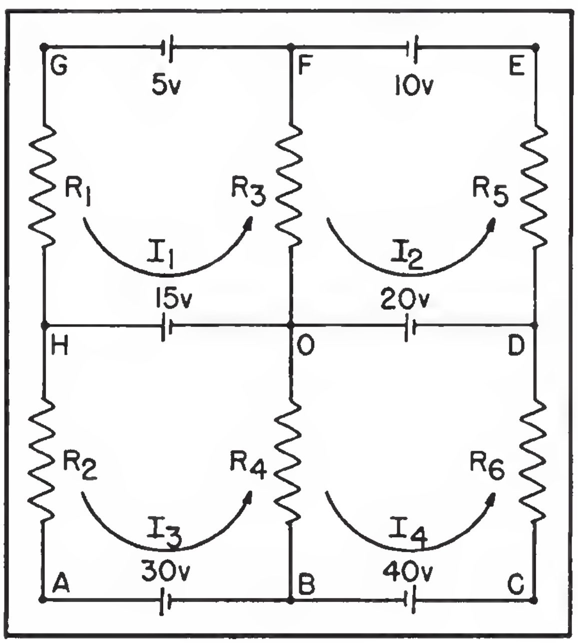

Figure 7-52

LOOP: HOFG: ABOH:

ODEF: BCDO:

14. Using loop analysis solve for the current through, and the voltage across each of the resistors in Figure 7-53.

E_{R1} = __________ I_{R2} = __________

E_{R1} = __________ E_{R3} = __________

E_{R2} = __________ I_{R3} = __________

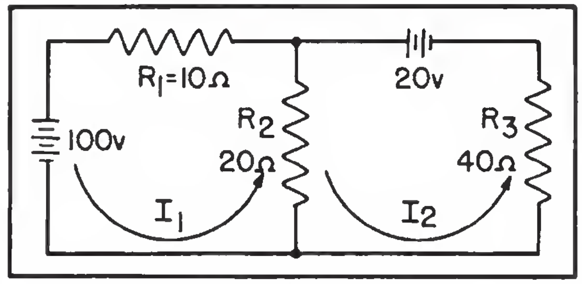

Figure 7-53

15. What value of resistance would an ohmmeter indicate if connected across any one of the 10 ohm resistors in Figure 7-54?

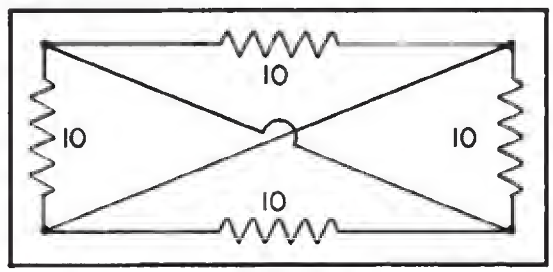

Figure 7-54

16. If one of the 10 ohm resistors in Figure 7-54 were to short, what would be the resistance between any two junctions in the network?

17. Develop a Thevenin's equivalent circuit for the network in Figure 7-55. Using the equivalent circuit compute the load voltage.

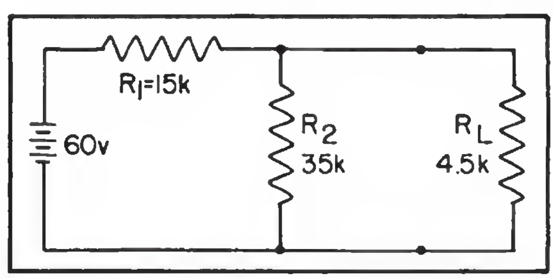

Figure 7-55

18. Thevenize the circuit in Figure 7-56 and solve for the load voltage.

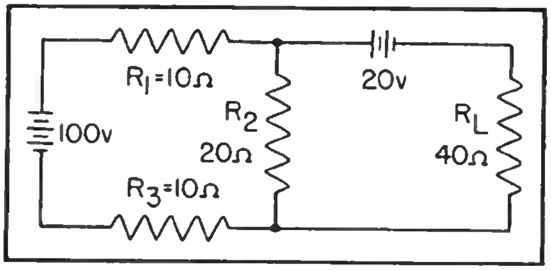

Figure 7-56

19. Develop a Norton's equivalent circuit for the network in Figure 7-56 and solve for the load current. (Hint: $I_n = \frac{E_{th}}{Z_{th}}$)

20. Using Figure 7-57 solve for the voltage and polarity at the first point listed with respect (w/r) to the second point listed.

A (w/r) C	D (w/r) K	J (w/r) C
I (w/r) B	G (w/r) I	K (w/r) A
D (w/r) H	C (w/r) L	B (w/r) F

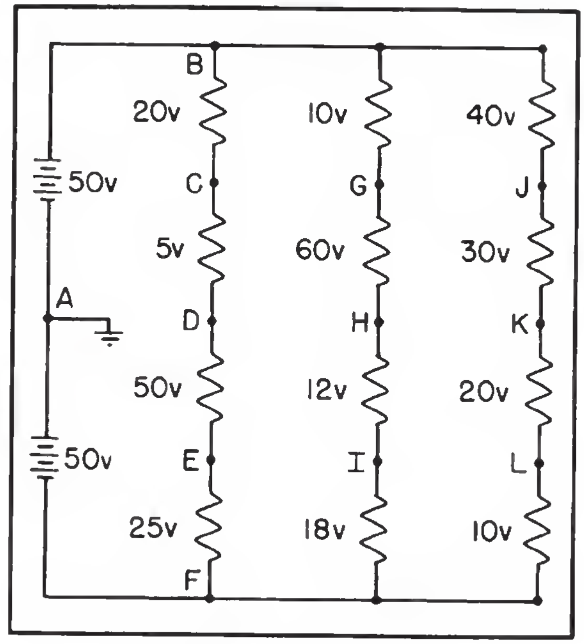

Figure 7-57

21. Find the current through, and the voltage across each resistor in Figure 7-58, and compute the total resistance and total current.

E_{R1} = ____	E_{R5} = ____	I_{R1} = ____	I_{R5} = ____
E_{R2} = ____	E_{R6} = ____	I_{R2} = ____	I_{R6} = ____
E_{R3} = ____	E_{R7} = ____	I_{R3} = ____	I_{R7} = ____
E_{R4} = ____	E_{R8} = ____	I_{R4} = ____	I_{R8} = ____
		R_t = ____	I_t = ____

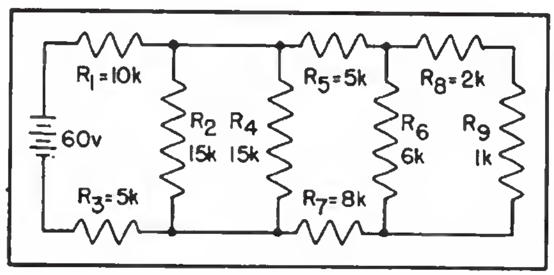

Figure 7-58

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